AF-82-01

Engine Block Heaters: An Evaluation of Their Energy Conservation Potential In Light-Duty Vehicles

T.Topaloglu
Research Officer
Automotive Energy Group

Published by:
The Transportation Technology and Energy Division
Ontario Ministry of Transportation and Communications
Hon. James W. Snow, Minister
H.F. Gilbert, Deputy Minister

Published without prejudice
as to the application of the findings.
Crown copyright reserved; however, this
document may be reproduced for non-commercial
purposes with attribution to the Ministry.

For additional copies write:
The Editor
Research and Development Branch
Ministry of Transportation and Communications
1201 Wilson Avenue
Downsview, Ontario
M3M 1J8

September 1982

ACKNOWLEDGEMENTS

The author would like to express his gratitude to Cecil Simmons and his staff for their valuable assistance in preparing the vehicles and in carrying out the fuel consumption and emissions tests.

All members of the Automotive Energy Group have contributed to this report with their comments and suggestions. I am especially indebted to Ovi Colavincenzo for his constant encouragement and support.

TABLE OF CONTENTS

	PAGE
ACKNOWLEDGEMENTS	ii
LIST OF TABLES	iv
LIST OF FIGURES	v
EXECUTIVE SUMMARY	vi
1/ INTRODUCTION	1
1.1/ Background.	1
1.2/ Objectives.	4
2/ EXPERIMENTAL DESIGN	6
2.1/ Vehicles and Vehicle Preparation.	6
2.2/ Fuel.	7
2.3/ Driving Cycle	7
2.4/ Instrumentation and Apparatus	8
2.5/ Test Procedure.	9
3/ EXPERIMENTAL RESULTS AND DISCUSSION	12
3.1/ Vehicle Fuel Consumption at Lower Ambient Temperatures.	12
3.2/ The Effect of Block Heating on Fuel Consumption	14
3.3/ Selection of Heating Period	17
3.4/ The Effect of Block Heating on Driveability and Exhaust Emissions.	19
3.5/ Economics of Block Heating.	21
4/ CONCLUSIONS	24
REFERENCES	25
TABLES	28
FIGURES	47

LIST OF TABLES

PAGE

1/ Vehicle Description 28

2/ Vehicle Preparation 29

3/ Test Fuel Specifications. 30

4/ Quantitative Description of Driving Cycle 31

5/ Fuel Consumption -- Ambient Temperature Correlation for Cold-Start Tests (Fuel Consumption Without Block Heaters). 33

6/ Fuel Consumption -- Ambient Temperature Correlations for Cold-Start Tests (Fuel Consumption With Block Heater). 34

7/ Sensitivity of Fuel Consumption to Ambient Temperature 35

8/ Cold-Start Excess Fuel Consumption Without Block Heaters 36

9/ Average Vehicle Fuel Consumption and Fuel Saving in Cold-Start Tests 37

10/ Estimates of Average Total Fuel Consumption and Total Fuel Savings. 38

11/ Cold-Start Idle Exhaust Emissions 39

12/ Fuel and Cost Savings per Cold-Start Under Average Winter Conditions in Southern Ontario 40

B.1-B.6/Fuel Economy Test Data with Block Heaters (One table per vehicle model tested). 41

LIST OF FIGURES

PAGE

1/ Test Route. 47

2/ Driving Cycle 47

3/ Fuel System Schematic 48

4 to 15/ Cold-Start Fuel Consumption as a Function of Ambient Temperature -- With and Without Block Heating (Two figures per vehicle model tested). 49-61

16 to 21/ Block Temperature Response to Heating (One figure per vehicle model tested) 62-68

A.1 to A.4/ Time-Variation of Vehicle and Engine Parameters During a Typical Cold-Start Test. 69-73

A.5 to A.8/ Time Variation of Vehicle and Engine Parameters During a Typical Warm-Start Test. 74-78

EXECUTIVE SUMMARY

Under winter conditions, the fuel efficiency of gasoline engine equipped light-duty vehicles deteriorates significantly. The excess gasoline consumption in Ontario directly caused by cold-weather conditions is estimated at 300 to 700 million litres per year. Most of this waste occurs over the warm-up phase of vehicle operation, i.e., during the first 8 to 10 km of a cold-start trip when vehicle components are striving towards their operating temperatures. Excess fuel consumption is accompanied by excess pollutant emissions and excess engine wear.

Judicial use of block heaters has been proposed as a means of reducing cold-weather excess fuel consumption and its accompanying problems. At present, block heaters are commonly used in Northern Ontario as starting aids. The usual mode of application is 11 to 13 h of overnight heating during October to March. In this mode, electricity consumption is excessive and its cost cannot be justified in terms of the resulting gasoline conservation. However, block heater application for a limited period of time may provide an economical way of substituting electricity for gasoline while realizing the benefits in improved driveability, engine and electrical component life, exhaust emissions and passenger comfort.

In order to assess the advisability of the above proposal, an extensive road test program was carried out with a fleet of 12 vehicles (ten automobiles and two vans) consisting of two specimens each of the following models: 1980 Chevrolet Citation, 1980 Pontiac Parisienne, 1979 GM Van, 1980 Ford Fairmont, 1979 Fort LTD and 1981 Dodge Aries. The most commonly available block heater (Temro 600 W heater) was applied for the two hours immediately prior to cold-starting. Fuel consumption, with and without block heater application, was measured on the same day, using two specimens of each model, over a typical 8 to 9 km city cycle. A total of 248 cold-start and 596 warm-start road tests were conducted over the ambient temperature range of +8°C to -20°C during winter 1980/81. In addition, the effects of block heating on cold-start idle exhaust emissions and vehicle driveability were assessed.

The results of the test program indicate that block heating for a limited period of time has significant oil conservation potential. Under winter conditions typical of Southern Ontario, fuel consumption with a cold vehicle is 30% to 50% greater than that with a warm vehicle. Two-hour heating with a 600 W block heater reduces this waste by 20% to 25%. More precisely, gasoline consumption during a cold-start trip at +8°C to -20°C is decreased by 100 to 200 mL, depending on engine type. The savings are greatest with larger eight-cylinder engines. In Ontario, if 50% of all light-duty vehicles were plugged in for 150 d/yr, an estimated 55 million litres of gasoline could be saved annually.

Application of block heaters for more than a few hours immediately prior to driving is unnecessary and wasteful. Experience with the test vehicles indicates that, in general, within two hours of heating, the block temperature approaches a steady-state level, on the average, 20°C - 30°C above the ambient temperature. Heating for a longer period will not, in general, result in a further significant temperature rise.

The fuel savings generated by block heating are sufficient to pay for the electricity consumption. In fact, in the case of eight-cylinder engines, a modest net benefit of $6 to 7/yr is expected. However, even in this case, the cost savings are not sufficient to fully amortize the purchase and installation of a block heater and timer. Thus, application of block heaters requires an initial investment -- part of which may not be recovered through gasoline savings alone. However, extended engine and electrical component life may make up for this deficiency. No test data have been accumulated in this program to quantify such long-term cost benefits. Instead, the benefits of block heating on vehicle starting and pollutant emissions were determined qualitatively.

In the range of -15 to -25°C, two-hour block heating enhanced vehicle starting significantly. In fact, in the case of one vehicle model, starting in the below -20°C range was impossible without the assistance of a block heater. The effect of heating on cold-start idle exhaust emissions was substantial. Hydrocarbon and carbon monoxide emissions were reduced by 44% and 27%, respectively. Although these results cannot be generalized, they are sufficient indicators of the pollution abatement potential of block heating.

1/ INTRODUCTION

The Transportation Energy Management Program (TEMP) was established in 1977 by the Ontario Government for reducing oil consumption in the transportation sector. It is administered by the Ministry of Transportation and Communications in co-operation with the Ministry of Energy.

TEMP's goal is to conserve crude oil by 10% above the level expected from the Corporate Average Fuel Economy (CAFE) standards by 1985. In order to direct efforts towards this goal, a number of subprograms have been introduced. The mandate of one of these subprograms, DriveSave, is to co-ordinate the development and distribution of information needed to improve the fuel economy of passenger vehicles in Ontario. One of the potential conservation areas under investigation in support of DriveSave is the reduction of cold-weather excess fuel consumption. Within this area, the use of electric engine block heaters in gasoline engine powered light-duty vehicles was studied during winter 1980/81 by performing a series of fuel economy tests and complementary experiments with 12 representative vehicles. This report is a documentation of the test results and their interpretation.

1.1/ Background

The fuel economy of road vehicles decreases significantly under cold-weather conditions. The amount of fuel wasted is especially large in gasoline engine equipped light-duty vehicles, viz., automobiles, vans and small trucks. Excess fuel consumption is accompanied by excess hydrocarbon and carbon monoxide emissions and by excess engine wear.

In recent years, the above problems have received greater attention by the research community and by society at large. A number of experimental studies have been conducted to quantify the extent of excess fuel consumption and exhaust emissions. Some of the results have been reported in References 1 to 12. However, little has been done to elucidate the mechanisms which contribute to this inefficiency and pollution problem. Similarly, little has been done to quantify the effectiveness of those measures that could reduce this problem. For instance, the utility of engine block heaters, automatic fan clutches and radiator

shutters in light-duty vehicles has not been thoroughly investigated. Only in one recent study [10] has the effectiveness of block heaters in reducing fuel consumption been systematically evaluated.

It is reasonably well established that the extent of excess fuel consumption due to lower ambient temperatures is a strong function of driving cycle and engine characteristics. The deterioration in fuel economy is most pronounced during the warm-up phase of a driving cycle. The fuel consumption of a fully warmed-up engine is only slightly affected by ambient temperature conditions. The data available in the literature indicate that the fuel consumption of automobiles increases by 10 to 20% over short trips (less than 8 km) and 2 to 3% over long trips (more than 25 km) as the ambient temperature drops from +25°C to +10° to -20°C [1 to 9]. It is estimated that in Ontario short trips constitute approximately 55% of all trips made by light-duty vehicles.

Engine type and engine size appear to affect the amount of fuel wasted. The fuel consumption of diesel engines is significantly less sensitive to ambient temperature. To a lesser extent, stratified-charge and lean-burn engines perform better than standard gasoline engines under low temperature conditions [2,3]. The extent of excess fuel consumption in larger engines is greater than that in smaller engines. However, on a percentage basis, the fuel consumption of smaller engines may be more sensitive to ambient temperature. According to the 1980 registration files, the cylinder number distribution in the Ontario passenger vehicle fleet was 22% 4-cyl., 22% 6-cyl. and 56% 8-cyl..

There are few published data quantifying the mechanisms that contribute to cold-weather excess fuel consumption. These are scattered in numerous publications and are difficult to reconcile and generalize. However, it is well-known that the main loss mechanisms are [13]:

- More choke application with cooler engines.
- Increased friction in the engine, rear axle, and transmission due to increased lubricant viscosity at lower temperatures.
- Greater combustion heat loss to the combustion chamber walls and coolant due to greater temperature differences. This results in lower engine thermal efficiency.
- Increased rolling friction in tires.

Cold-weather excess fuel consumption is most severe during the period when the temperature of the coolant, engine oil, transmission fluid and differential oil are striving towards their equilibrium levels. Among these, the coolant and engine oil temperatures reach their equilibrium values most quickly, while the transmission and differential respond rather slowly. Under equilibrium conditions, fuel consumption is still sensitive to ambient temperature, since component equilibrium temperatures depend on ambient temperature. This sensitivity, defined as component equilibrium temperature change per degree change in ambient temperature, was found to be 0.7 for the transmission, 0.5 for the differential, 0.3 for the engine oil, and 0.2 for the coolant [4]. Foregoing results were obtained in chassis dynamometer tests where aerodynamic conditions were simulated by providing an air flow into the frontal area of the vehicle at a speed proportional to vehicle speed. However, radiant heat loads and road surface effects were not simulated. Consequently, the correlation of measured temperature profiles to actual profiles experienced in road use is not known.

In road tests performed by the U.K. Road Research Laboratory [7], steady-state fuel consumption was not found to be noticeably dependent on ambient temperature. In this study, transient excess fuel consumption was measured with a car and minibus. The average warm-up period for these vehicles was estimated at 15 min.

The effect of ambient temperature on exhaust emission levels from typical North American automobiles has been well researched [1 to 5, 1 to 12]. The results of these efforts indicate that, under cold-weather conditions, carbon monoxide and hydrocarbon emissions rise significantly during the warm-up phase of driving. In fact, at -20°C, typical gasoline engines were found to emit five to six times more carbon monoxide and hydrocarbons than allowed by the Canadian emission standards [3]. Oxides of nitrogen emissions, on the other hand, are relatively insensitive to ambient temperature.

Experimental results correlating engine wear directly to ambient temperature could not be found in the open literature. However, the effect of coolant temperature on engine wear is reasonably well established [23,24]. Engine wear, especially at piston rings, increases strongly at

lower coolant temperatures. This effect may be mitigated by adopting measures that accelerate engine warm-up, e.g., block heaters, radiator shutters and modulated fans.

The utility of engine heaters as cold-weather starting aids is well-established. Electric, in-block immersion heaters are widely used in most types of gasoline and diesel engine driven road vehicles in the colder areas of Canada. In addition to facilitating vehicle starting, they provide significant operating and maintenance cost savings, especially in heavy-duty vehicles, by extending engine and electrical component life and by reducing idling periods [25,26].

It has been claimed that block heaters may also conserve energy if their utilization or plug-in period is limited to colder days and to a few hours per cold-start. This mode of application, which may be facilitated by the use of electric timers and/or thermostats, has not been thoroughly investigated. The only detailed published study on the energy conservation of block heaters is that of the National Swedish Road and Traffic Research Institute, who performed road tests with a Saab 99 (1973 model) and a Saab 95 (1974 model) on a combined suburban/highway driving cycle [10]. On this test cycle an average fuel saving of 0.12 L of gasoline was measured over the period of November 1 to March 31 in Sweden. On the basis of their detailed results, they recommended block heater application for 3 h at below -15°C, for 2 h at -15°C to -5°C, and for 1 h at 5°C to +15°C.

1.2/ Objectives

The study was intended to provide quantitative information on the utility of block heaters under winter conditions in southern Ontario. For greater applicability, the assessment had to involve road testing with a small fleet of vehicles representative of the near-term trends.

The utility of the block heater in reducing fuel consumption and pollutant emissions and in improving vehicle driveability had to be evaluated. In order to perform this function, the following concrete objectives were set for the test program:

- Determine the extent of cold-weather excess fuel consumption in urban driving under cold-start and warmed-up operating conditions. Assess the sensitivity of vehicle fuel consumption to ambient temperature and engine size.

- Determine the level of fuel savings with 2 h of block heater application under both cold-start and warmed-up vehicle operating conditions. In order to complete this phase of the program during winter 1980/81, testing was limited to 2 h of heating with 600 W block heaters.

- Determine actual electricity consumption with each block heater used during the full application period. Deduce net energy and cost savings due to the application of block heaters for each vehicle tested.

- Assess the effect of block heater application on CO and HC exhaust emissions.

- Identify those mechanisms contributing to excess fuel consumption, assess their relative significance and propose means of mitigating their effects.

2/ EXPERIMENTAL DESIGN

The experiments were designed to satisfy the objectives of the project at a minimum cost. These objectives necessitated measurement of vehicle fuel consumption with and without a block heater over a typical urban driving cycle and over a low temperature range available during winter 1980/81. In addition, the rate of temperature rise in the coolant and idle HC and CO emissions with and without block heater application had to be established.

Fuel consumption tests with block heaters require a number of special considerations. The effect of block heaters is greatest during the first 5 to 10 km of a trip driven from a cold-start. Consequently, cold-start tests had to be conducted with a vehicle that had been at rest under ambient conditions for 12 to 36 h prior to testing. This limited the number of tests with a given vehicle to one per day and necessitated testing two identically-specified vehicles each day. One of these was not heated and served as a standard or baseline vehicle while the other was heated for 2 h prior to starting.

The utility of block heaters was expected to increase with decreasing ambient temperature. Therefore, whenever possible, testing was limited to the colder days of winter 1980/81. Days of heavy rain and snow were avoided. These requirements made testing on a remotely located test track very inefficient and expensive. Consequently, testing was conducted on city streets around the MTC complex with pairs of vehicles being driven on the same day. Tests conducted on an urban schedule were expected to produce more representative results, since the most prevalent mode of driving immediately following a cold start involves urban routes.

The main elements of the test methodology were outlined above. In the following subsections the test equipment and procedures will be described in greater detail.

2.1/ Vehicles and Vehicle Preparation

Six pairs of vehicles were tested in this program -- five pairs of automobiles and one pair of vans -- whose pertinent specifications are

listed in Table 1. The eight- and six-cylinder engine equipped vehicles are representative of conventional driveline technology while the four-cylinder engine equipped ones are front-wheel driven and are expected to become forerunners of the dominant near-term technology. Six of the vehicles tested were leased from commercial agencies while two were obtained from the Ontario Provincial Police and four from MTC. Care was taken in selecting vehicles which had been run for a minimum of 3200 km and were in good running condition. Immediately subsequent to their acquisition all vehicles were checked and if necessary, set to manufacturers' specifications with respect to the items listed in Table 2. This check was repeated at the end of the test program and all vehicles were found to have remained within manufacturers' specifications. A "Sun" (Model 945/947) infrared engine performance tester was used for diagnosis and adjustments.

Subsequent to the initial inspection, each test vehicle was equipped with a 600 W block heater, an auxiliary fuel line and a fuel tank. Next, the vehicle mass was determined and if necessary, adjusted such that two twin vehicles were within 50 kg.

2.2/ Fuel

During the entire test program, fuel from the same batch of winter grade gasoline stored in an MTC research fuel tank was used. Pertinent fuel specifications for this batch of gasoline are listed in Table 3.

2.3/ Driving Cycle

The driving cycle for tests to be carried out on city streets is dictated by the choice of the test route. In this study, this route was selected to satisfy the criteria of test repeatability and representativeness. The final 8.815 km route that was followed with all vehicles except the vans is indicated on the map in Figure 1, and the resulting driving cycle is presented in Figure 2. The driving cycle was recorded in many tests carried out with two instrumented test cars (Ford Fairmonts). The resulting speed-time profiles were analyzed on the computer to produce a quantitative description of the test cycle in terms of time spent in

various speed and acceleration/deceleration ranges. The results of a representative test are presented in Table 4. This procedure was repeated several times at the beginning of the test program, in order to assess the precision with which the driving cycle could be repeated by the test driver.

Each test with a given vehicle involved repetition of the above-described driving cycle three times. The first cycle represents cold-start operation, while the two subsequent ones represent partially or fully warmed-up vehicle operation. A total distance of 26.445 km was covered, on the average, in 42.9 min during each test. Testing with the vans was carried out on a slightly extended route of 9.316 km. In this case, a total distance of 27.900 km was covered, on the average, in 44.3 min.

2.4/ Instrumentation and Apparatus

Of the 12 vehicles employed in this study, the two Ford Fairmonts were extensively instrumented. These two vehicles were equipped to monitor the temperature of the coolant at the front and back of the block, the temperature of the air in the underhood and at the inlet of the carburetor, the engine oil temperature in the sump, the vehicle speed, the manifold vacuum, the engine speed, the fuel flow rate, and the choke position. The transducer outputs were recorded on a magnetic tape and subsequently processed to produce variable-time profiles. Examples of these profiles are provided in Appendix A in Figures A.1 to A.4 for a cold-start test cycle and in Figures A.5 to A.8 for a warm-start test cycle. In this study, these data were utilized only qualitatively. Therefore, details of this instrumentation and its application will not be presented here. In order to measure vehicle fuel consumption accurately and quickly, all vehicles were equipped with auxiliary fuel lines and fuel tanks. The equipment employed is schematically described in Figure 3. It allowed for quick connection and removal of fuel tanks which can be weighed before and after each test to measure total fuel consumption. Its use does not affect fuel metering significantly, since the original carburetor and fuel pump are employed and the auxiliary fuel line and fuel tank do not alter flow resistance. The auxiliary fuel lines have the same nominal inside diameter as the original lines and the fuel tanks are vented to the atmosphere. The fuel weight was measured with a

Mettler PT 15 electronic scale that has a 0.1 g resolution. The accuracy of the scale was assessed by calibration checks and was found to be well within 1 g. In measuring the electricity consumption of the block heaters a Simpson 390-2 Wattmeter was employed.

The heating rate of the block under block heater application was measured with a Wahl DHS-14X "heat spy" infrared thermometer. The idle HC and CO concentrations were measured with the infrared exhaust gas analyzer, Model U-912-1, on the "Sun" engine performance tester.

2.5/ Test Procedure

The experimental evaluation of block heaters entailed four basic steps.

- Preparation of vehicles and test equipment.
- Measurement of engine warm-up and electricity consumption rates under block heater application.
- Determination of vehicle fuel consumption with and without block heaters (fuel consumption tests).
- Measurement of idle exhaust emissions with and without block heater application.

Of the above steps, only the fuel consumption tests require further description in this section. These were devised to meet the special requirements of cold-start testing on city streets -- a problem which is not addressed in its entirety in test procedures devised by the Society of Automotive Engineers and Transport Canada.

Testing was carried out in a paired vehicle mode. Baseline and test vehicles were driven by the same driver over the same driving cycle within half an hour, but not simultaneously. Specifically, each of the twin vehicles of a given model were driven over the same cycle every day and were parked side-by-side in front of a one-storey structure, ready for next day's testing. The block heater on the test vehicle was plugged into a timer set to initiate heating 2 h prior to test driving. By driving and parking each vehicle for the same period and in the same manner, test precision was enhanced. The parking site simulated common outdoor parking conditions.

Each morning, following a soak period of 16 to 20 h, three auxiliary fuel tanks (canisters) were weighed and placed outdoors, where fuel evaporation rates under cold-weather conditions are negligible. Tire pressures on both vehicles were checked and adjusted and the weather data were recorded. Next, one of the auxiliary tanks was placed into the trunk of the test car, the fuel line was connected, and the vehicle was driven over the first test cycle. At starting, the idling period was limited to 30 s, unless starting problems developed. Vehicle driveability was assessed and recorded in qualitative terms. Driving was carried out with as much consistency as possible in order to achieve test-to-test and day-to-day comparability. Traffic and road conditions were recorded, such that the reliability of the test could be assessed more readily at the data analysis stage.

At the end of the test cycle, the vehicle was parked at the same site and the engine was idled for 30 s before being stopped. This last step was intended to reduce the test-to-test variability in the state of the fuel lines and the carburetor. The test tank was removed from the test car, weighed, and placed into the baseline car. Thus, the same tank was used in the two vehicles for a given pair of comparative tests.

Within 15 to 20 min of the first test, the same test cycle was driven with the baseline car. Block heater and baseline tests were alternated three times. Testing with one pair of vehicles took 1.5 to 2.0 h. At the end of the test sequence the three canisters were weighed and refilled for the afternoon tests to be conducted with a second pair of vehicles.

Due to space and manpower limitations, only two pairs of vehicles could be tested each day. The only exception to this rule was the testing with the two Ford Fairmonts, which were equipped with accurate fuel flow meters. Testing with a given pair of vehicles was repeated until 15 to 25 successful tests were accumulated. With each pair, the test and baseline roles were alternated between vehicles in a manner to complete approximately the same number of tests with each of the two possible vehicle combinations. This procedure provides a better means of accounting for vehicle-to-vehicle fuel economy differences.

The fuel consumption of each vehicle was measured gravimetrically. These measurements were converted to a volumetric basis by using the density of the fuel at the prevailing ambient temperature. The resulting fuel consumption data for the test and baseline vehicles over all three test cycles are tabulated in Appendix B along with the test number, test date, test vehicle identification, and the average ambient temperature over the duration of the test.

3/ EXPERIMENTAL RESULTS AND DISCUSSION

In this section the experimental data on vehicle fuel consumption with and without block heating is presented. These data are interpreted to estimate the extent of fuel waste under low-temperature conditions and the effectiveness of block heaters in reducing this waste. In addition, experimental results quantifying idle exhaust emissions with and without block heating, vehicle warm-up characteristics and block heater electricity consumption are summarized and discussed. These results are drawn upon to assess the overall utility of block heaters and to propose more efficient and cost effective ways of reducing gasoline consumption.

3.1/ Vehicle Fuel Consumption at Lower Ambient Temperatures

The fuel consumption of the test vehicles was measured individually over three test cycles that were repeated at approximately 30 min intervals on each test day. The first cycle represents cold-start driving while the two subsequent ones represent various degrees of warm-start driving.

The test data summarized in Appendix B indicate that fuel consumption over the initial test cycle, i.e., during cold-start trips, is strongly dependent on ambient temperature. This observation is demonstrated by Figures 4 to 15 where cold-start fuel consumption with and without block heater application is displayed as a function of average ambient temperature over the test period. No definitive trends could be identified in the data accumulated over the subsequent test cycles.

The cold-start fuel consumption data were correlated linearly with temperature. The resulting least squares lines are provided in Figures 4 to 15 and the correlation equations and coefficients are summarized in Tables 5 and 6, along with the temperature range and average temperature at which the data were collected. The success of this approach may be judged by considering the magnitude of the correlation coefficient, r^2, which falls in the range of 0.78 to 0.96, except for one case. Chassis dynamometer test data obtained at the U.S. Department of Energy Bartlesville Research Centre [4] have also been correlated linearly with

temperature, while road test data obtained at the National Swedish Road and Traffic Research Institute [10] have been presented as slightly non-linear fuel consumption-ambient temperature plots. The fuel consumption correction factor prescribed in the SAE road test procedure [27] is based on a linear dependence of fuel consumption on ambient temperature. Although there is no theoretical basis for the linear dependence, the amount and quality of the data available for each vehicle do not justify a more complex relation. The relatively large scatter of the data around the correlation lines is typical of road test results. The main contributors to day-to-day fuel consumption changes are the variations in wind conditions, ambient temperature, road surface conditions and traffic conditions. Among these, ambient temperature is the only test variable whose fuel consumption effect is being studied. The process of curve fitting serves to smooth the data, i.e., to reduce the contribution of uncontrolled and unaccounted test variables. Deductions made on the basis of the correlations in Tables 5 and 6 rather than individual measurements are less likely to be biased by the influence of uncontrolled test variables.

The information presented in Table 5 can be directly used to estimate for each vehicle the sensitivity of fuel consumption to ambient temperature over the 8.815 km (9.300 km) cold-start trip. This is provided by the partial derivative of fuel consumption with respect to temperature, δ (FC)/δ T. In order to enhance the utility of this information, the data are normalized with respect to distance. The resulting sensitivity figures are provided in Table 7 for both the baseline and test cases. The fuel consumption sensitivity expresses change in fuel consumption per distance travelled for 1°C change in temperature expressed in terms of mL/km °C or %/°C. In every case the sensitivity figure is based on the average performance of two specimens of each model.

The baseline fuel consumption-temperature sensitivities measured in this study are in reasonably good agreement with those presented by the U.S. Department of Energy researchers [4], who have tested four 1977 U.S. automobiles on a chassis dynamometer at -7°C to +24°C. In this temperature range the average sensitivity figures for the four vehicles tested were -2.0, -1.3 and -1.0 mL/km °C for 6, 12 and 18 km driving, respectively.

3/ EXPERIMENTAL RESULTS AND DISCUSSION

In this section the experimental data on vehicle fuel consumption with and without block heating is presented. These data are interpreted to estimate the extent of fuel waste under low-temperature conditions and the effectiveness of block heaters in reducing this waste. In addition, experimental results quantifying idle exhaust emissions with and without block heating, vehicle warm-up characteristics and block heater electricity consumption are summarized and discussed. These results are drawn upon to assess the overall utility of block heaters and to propose more efficient and cost effective ways of reducing gasoline consumption.

3.1/ Vehicle Fuel Consumption at Lower Ambient Temperatures

The fuel consumption of the test vehicles was measured individually over three test cycles that were repeated at approximately 30 min intervals on each test day. The first cycle represents cold-start driving while the two subsequent ones represent various degrees of warm-start driving.

The test data summarized in Appendix B indicate that fuel consumption over the initial test cycle, i.e., during cold-start trips, is strongly dependent on ambient temperature. This observation is demonstrated by Figures 4 to 15 where cold-start fuel consumption with and without block heater application is displayed as a function of average ambient temperature over the test period. No definitive trends could be identified in the data accumulated over the subsequent test cycles.

The cold-start fuel consumption data were correlated linearly with temperature. The resulting least squares lines are provided in Figures 4 to 15 and the correlation equations and coefficients are summarized in Tables 5 and 6, along with the temperature range and average temperature at which the data were collected. The success of this approach may be judged by considering the magnitude of the correlation coefficient, r^2, which falls in the range of 0.78 to 0.96, except for one case. Chassis dynamometer test data obtained at the U.S. Department of Energy Bartlesville Research Centre [4] have also been correlated linearly with

temperature, while road test data obtained at the National Swedish Road and Traffic Research Institute [10] have been presented as slightly non-linear fuel consumption-ambient temperature plots. The fuel consumption correction factor prescribed in the SAE road test procedure [27] is based on a linear dependence of fuel consumption on ambient temperature. Although there is no theoretical basis for the linear dependence, the amount and quality of the data available for each vehicle do not justify a more complex relation. The relatively large scatter of the data around the correlation lines is typical of road test results. The main contributors to day-to-day fuel consumption changes are the variations in wind conditions, ambient temperature, road surface conditions and traffic conditions. Among these, ambient temperature is the only test variable whose fuel consumption effect is being studied. The process of curve fitting serves to smooth the data, i.e., to reduce the contribution of uncontrolled and unaccounted test variables. Deductions made on the basis of the correlations in Tables 5 and 6 rather than individual measurements are less likely to be biased by the influence of uncontrolled test variables.

The information presented in Table 5 can be directly used to estimate for each vehicle the sensitivity of fuel consumption to ambient temperature over the 8.815 km (9.300 km) cold-start trip. This is provided by the partial derivative of fuel consumption with respect to temperature, δ (FC)/δ T. In order to enhance the utility of this information, the data are normalized with respect to distance. The resulting sensitivity figures are provided in Table 7 for both the baseline and test cases. The fuel consumption sensitivity expresses change in fuel consumption per distance travelled for 1°C change in temperature expressed in terms of mL/km °C or %/°C. In every case the sensitivity figure is based on the average performance of two specimens of each model.

The baseline fuel consumption-temperature sensitivities measured in this study are in reasonably good agreement with those presented by the U.S. Department of Energy researchers [4], who have tested four 1977 U.S. automobiles on a chassis dynamometer at -7°C to +24°C. In this temperature range the average sensitivity figures for the four vehicles tested were -2.0, -1.3 and -1.0 mL/km °C for 6, 12 and 18 km driving, respectively.

It is also useful to compare the sensitivity figures obtained here with those proposed in the SAE J1256 "Cold Start and Warm-up Fuel Economy" test procedure [27]. Over a 6.4 km cold-start test cycle and for the temperature range of -1°C to +32°C, SAE proposes a correction factor that is based on an average sensitivity of -0.8%/°C. This is in reasonably good agreement with the data in Table 7.

The difference in fuel consumption between that of a "cold" engine and "warm" engine, commonly referred to as cold-start excess fuel consumption, is an indicator of the maximum potential for fuel economy improvement. This potential was assessed in this study by comparing the average fuel consumption of each vehicle during the first and second cycles to that during the third cycle. This method is based on the experimental observation that, during the third cycle, fully warmed-up vehicle operation is approached. The results of this analysis in Table 8 indicate that 30 to 48% more fuel is consumed during the first cycle, (viz., the cold-start cycle) than during the third cycle. The level of excess fuel consumption during the second cycle is not significant. These estimates do not pertain to a specific ambient temperature range, since they are based on the average of the daily experimental results of this study. Consequently, they cannot be generalized.

3.2/ The Effect of Block Heating on Fuel Consumption

The effect of block heating with 600 W immersion type heaters was assessed by comparing the fuel consumption of baseline and block-heated vehicles in cold-start and warm-start driving. The block heater application period was limited to 2 h immediately prior to cold-starting.

As noted in Section 3.1, only cold-start fuel consumption is strongly dependent on ambient temperature. As a result, only during this phase of vehicle operation can the use of block heaters contribute to major fuel savings. The experimental data in Figures 4 to 15 represent the savings observed during the cold-start tests with each vehicle over the ambient temperature range prevailing during the test period. At any temperature, the vertical separation between the regression lines for the base line and block-heated vehicles is an indicator of the fuel savings observed over the 8.8 km (9.3 km) cold-start trip. A better estimate can be obtained by considering the fuel savings obtained with both specimens of

each vehicle model, i.e., by considering the two graphs presented for each vehicle model. This process allows accounting for fuel economy differences between two specimens of a given vehicle model. It is more difficult to account for the test variability arising from the presence of uncontrolled and unaccounted test conditions, such as wind, traffic and road surface conditions. The uncertainty introduced into the data by these variables is quantified by the 90% confidence limit intervals provided in Figures 4 to 15. One can state, with 90% confidence, that the true fuel consumption of the baseline and test vehicles lie within the confidence limit envelopes drawn. In those cases where the two regions defined by these envelopes are not overlapping, one can assert with 90% certainty that the true fuel consumption of the block-heated vehicle is distinctly different from that of the baseline vehicle.

Estimates for the fuel saving potential of block heating in cold-start short trips at 0°C to -20°C were obtained by using the fuel consumption-temperature correlations in Tables 5 and 6. This approach produces average fuel saving estimates for each vehicle over a common temperature range, viz., 0°C to -20°C. It should be noted that in some cases extrapolation of the data is involved.

The results of this analysis, viz., the fuel consumption of the baseline and block-heated vehicles and the associated fuel savings are provided in Table 9. Accordingly, the 2 h application of a block heater is expected to result in 64 mL to 173 mL of fuel savings on an 8.8 km (9.3 km) cold-start trip, depending on the vehicle considered. These savings correspond to 3.8% to 8.1% of fuel consumed during this trip. The expression of savings as amount of fuel saved per cold-start is far more useful than as percent of fuel consumed, since this latter quantity depends on the total trip length and does not directly translate into cost savings. It should be noted that the largest relative and absolute fuel savings in Table 8 do not pertain to the same vehicle.

The data summarized in Table 8 relate to the first test cycle and may be employed to predict the magnitude of fuel savings expected in cold-start trips of about 10 km in length. It is fair to ask whether one could observe substantially greater savings in longer trips. The potential for accumulating further savings should depend on the rate at which vehicle

components reach their steady-state temperatures and on the differences between summer and winter steady-state temperature levels. Clearly, the values of these parameters will depend, among other things, on the specifics of ambient conditons, the driving cycle and vehicle design. The temperature-time data obtained in this study indicate that the engine oil temperature (a key parameter affecting vehicle fuel consumption) does not attain its steady-state value during the first test cycle at lower ambient temperatures and its steady-state value depends on ambient conditions. Consequently, some additional savings are expected in longer trips. The level of incremental savings cannot be predicted by using the limited amount of temperature-time data generated during this study. However, a reasonable estimate of the aggregate fuel savings can be produced by considering the fuel consumption measurements for the second and third test cycles.

As indicated in Section 3.1, the fuel consumption data of the second and third test cycles do not reveal a clear temperature dependence. As a result, for these two cycles the average savings were estimated by averaging the daily savings observed with each vehicle. It should be noted that these estimates do not represent true averages with respect to a temperature range, specifically 0°C to -20°C. However, the bulk of the experimental data fall into this temperature range and cover this range relatively well. Consequently, the estimated average savings should be representative of the 0°C to -20°C conditions. A second point to be noted is that the total trips including the three test cycles involve two major stops (approximately half an hour each). Those two stops reduce the potential of block heating since during these periods the block-heated engine loses more heat than the baseline engine, resulting in a smaller difference between the two engines. Thus, the average savings reported here are expected to be conservative estimates.

Total savings estimates were obtained by adding the second and third cycle averages to the estimates for the first cycle, i.e., the cold-start cycle. The results are presented in Table 10. These are conservative estimates for the maximum fuel savings attainable per cold-start for the vehicles tested and over the ambient temperature range of 0°C to -20°C.

The data in Table 10 indicate that the total savings with the three eight-cylinder engines tested is around 0.2 L and that savings with the two four-cylinder ones is around 0.1 L. The saving observed with the six-cylinder engine (Ford Fairmont engine) is unusually low and may not be representative of all six-cylinder engines. With both Ford Fairmonts tested in this project, engine oil consumption was in excess of 1 L/500 km despite the fact that 18 000 km and 20 000 km had been accumulated prior to the initiation of this project. This high level of oil consumption is indicative of larger than usual gaps between piston rings and cylinder walls. This condition would have resulted in a reduced sensitivity of fuel consumption to engine oil viscosity and, therefore, a reduced effectiveness of block heating.

Above results are in good agreement with those of the National Swedish Road and Traffic Research Institute [10]. In their extensive road test program on a 34 km test circuit with two four-cylinder Saab engines of 1.5 L and 2.0 L capacity, 0.1 to 0.2 L of fuel savings were observed in cold-start driving at below 0°C. These savings were achieved with 1 to 3 h application of 520 W block heaters. More specifically, at 0°C the 2 L engine was found to consume 0.3 L of extra fuel to reach its running temperature of approximately 0°C. A 2 h application of the block heater in this engine raised the temperature of the block to approximately +20°C and reduced fuel consumption by 0.18 L, viz., a fuel saving of 0.12 L.

3.3/ Selection of Heating Period

The selection of the heating period depends on the final objective of heating. Specifically, the following three objectives were considered in this study: maximization of net energy savings, total gasoline savings, and cost-effectiveness to the consumer. The final choice was a combination of these, viz., maximize total gasoline savings while minimizing any net energy and monetary losses.

The heat provided by the block heater to the water in the cooling jacket is transferred rather quickly to engine components (block, head, cylinders, etc.) including the lubrication on these components. Simultaneously, yet more slowly, heat is lost by convection and radiation from these components to the surroundings, mainly the ambient air. Initially, this

dynamic process leads to a rise in the temperature of the engine. However, as the engine becomes warmer, heat transfer rates to the surroundings increase until the rate of heat addition is equal to the rate of heat loss. This steady-state condition will continue until there is a change in the surroundings or the system. Thus, with any engine/block heater combination one expects a unique temperature profile at a given set of ambient conditions, which displays an initial phase of fast temperature rise, followed by a slower temperature rise culminating in a constant steady-state temperature distribution. Clearly, block heating should be limited to the time it takes to reach steady-state. Any further heating would only result in an energy loss. In case the temperature level afforded by this practice is inadequate, the block heater may be changed. Furthermore, higher temperatures may be achieved by parking the vehicle in a sheltered area. Under windy conditions, heat transfer rates to the atmosphere increase significantly, resulting in a major reduction of the block heater's effectiveness.

Net energy consumption is minimized by operating the block heater for the minimum period necessary to reach steady-state. Estimates for this period were obtained by monitoring the block temperature of each engine tested under typical ambient conditions. The results are presented in Figures 16 to 21. It appears that at 0°C to -10°C, steady-state conditions are approached in approximately 2 h. In the first hour of heating, the temperature of the smaller engines rises by 15 to 25°C while that of the larger engines rises by 10 to 20°C. Thus, in most cases, approximately 75% of the heating occurs during the first hour. These results are in good agreement with those reported in Reference 10. A heat balance for a typical eight-cylinder engine with 135 kg of mass and 5 L of water in the cooling jacket indicates that during the 2 h heating period less than 50% of the electrical energy supplied contributes to the temperature rise and the remainder is lost to the surroundings. The temperature gradient observed between the block-heated side and the other side of the engine (see Figures 16 to 21) is an indicator of relative rates of heat transfer to the block and away from it.

Although the above tests are inadequate to predict engine warm-up times over a large temperature range, they are sufficient to indicate that heating beyond 2 h will be rather inefficient, with the exception of operation at very cold ambient conditions. Consequently, all fuel

consumption testing was performed with 2 h of block heating. Further experimentation with different heating periods would have been useful in assessing the feasibility of reducing the heating period without significantly increasing fuel consumption. The experimental data presented in Reference 10 indicate that a reduction of the heating period from 3 h to 1 h reduces fuel savings by approximately 30% at 0°C and above and by approximately 50% at -10°C and below. Hence, for most winter days, the block heater should be plugged in for 2 h. Only under milder weather conditions, viz., warmer than +5°C, should block heating be restricted to one hour.

3.4/ The Effect of Block Heating on Driveability and Exhaust Emissions

It is well-known that the ambient temperature has a large effect on cold-start driveability and exhaust emissions. The block heater is, in fact, a device primarily intended to solve the cold-weather driveability problem -- mainly in starting but also during warm-up. Its effectiveness in this area is well established. Its utility in reducing exhaust emissions, on the other hand, does not appear to be documented. A literature search conducted for this study could not discover any information dealing with the effect of block heating on exhaust emissions.

During the warm-up phase of an SI-engine, hydrocarbon (HC) and carbon monoxide (CO) emissions may increase by a factor of three to four as the ambient temperature drops from +20°C to -5°C [4]. Emissions of oxides of nitrogen, NO_x, on the other hand, display only a slight dependence. Warm-up phase emissions of HC and CO constitute a major portion of all HC and CO emitted by transportation vehicles [5]. Consequently, reduction of this problem will contribute very effectively to pollution abatement, especially under cold-weather conditions.

The assessment of the effect of block heating on HC and CO emissions was performed in this study by measuring cold-start idle exhaust emissions with and without block heating each of the vehicles tested. Simultaneously, the carburetor choke position was followed. Measurement of emissions over the driving cycle would have been preferable, however, lack of portable emissions analyzers and personnel precluded such an undertaking. Instead, the concentrations of HC in p.p.m. and CO in percent were measured with an infrared analyzer in 1-min. intervals immediately after

starting. With most vehicles, emission levels were found to approach steady-state in 5 min. Consequently, the average of the readings over these 5 min was taken to represent average cold-start idle exhaust emission concentrations. This procedure was carried out with both specimens of each model with and without block heating. The average of the results with the two specimens of each vehicle model are reported in Table 10. It should be noted that, due to soak period requirements, emissions testing with a given vehicle took two work days to complete and the test temperatures provided in Table 10 are averages of the ambient temperatures prevailing during measurement period on these two days.

The results in Table 10 indicate that, in general, cold-start idle exhaust emissions are very high. This observation reflects the effect of cold-starting and lower ambient temperatures on HC and CO emissions. In conventional idle emission tests, which are carried out at room temperature (+20 to 25°C) with fully warm engines, the emission levels are, in general, at least a factor of three to four lower -- especially with vehicles set to manufacturers' specifications [28].

The data in Table 10 also indicate that the block heater is indeed very effective in reducing idle exhaust emissions. For the population of vehicles tested, we observe that the average HC concentration dropped from 501 p.p.m. to 284 p.p.m. (44% improvement) and the CO concentration dropped from 3.7% to 2.7% (27% improvement). These improvements in idle emissions are impressive, especially when absolute changes in concentration are considered. However, these figures do not directly reflect cycle emissions, i.e., the amount of pollutants emitted per distance travelled on a driving cycle where idling constitutes only a minor phase of the total vehicle operation. The relation between idle emissions and cycle emissions is being actively investigated. It appears that although idle emissions cannot be readily translated into cycle emissions, the trends observed in idle emissions do reflect trends observed in cycle emissions. During driving, where engine speed is higher and the air-fuel mixture is leaner, HC and CO emissions are much lower than during idling. Consequently, in terms of absolute concentrations, the block heater will be less effective. However, it will still provide a significant reduction in the total amount of pollutants emitted.

The effectiveness of the block heater in reducing HC emissions can be explained readily. HC emissions are largely due to the fact that some of the fuel in the thermal boundary layer on cylinder walls cannot be reached by the flame and therefore remain uncombusted. The flame is quenched by the cooler boundary layer gas. The thickness of the boundary layer is a function of the cylinder wall temperature. Block heating is directly effective in reducing the thickness of the boundary layer and thereby the amount of HC exhausted. A second reason for HC emissions is the lack of sufficient oxygen to burn all fuel in the cylinders. This occurrence is most prevalent during cold-starting when the air-fuel mixture is rather rich in fuel. Block heating may reduce application of the choke and thereby help reduce mixture enrichment. However, results of monitoring the choke position during emissions testing did not indicate a major effect of block heating.

The effectiveness of the block heater in reducing CO emissions is more difficult to explain. CO emissions are primarily a result of incomplete combustion in the engine and in the converter. Incomplete combustion is caused mainly by a lack of sufficient oxygen but is also due to a lack of energy to convert CO to CO_2. Thus, CO emissions are largely a function of the mixture composition and therefore, increase significantly during cold-starting. The block heater may reduce CO production by decreasing mixture enrichment. A second mechanism may involve conditions in the converter. By reducing HC emissions the block heater will cause two changes in the converter: greater availability of oxygen and lower temperatures. Excess oxygen will result in higher CO to CO_2 conversion rates. Lower temperatures, on the other hand, will reduce the conversion rates. More specific experimentation is required in order to predict the net effect of this and other possible mechanisms through which block heating may affect emissions.

3.5/ Economy of Block Heating

The findings of this report may be used to assess the benefits of block heating as a fuel conservation measure. Detailed economic analysis is beyond the scope of this report. Only a simple cost-benefit analysis will be provided here in order to illustrate the attractiveness of the measure to the consumer and the province. In this analysis the utility

of block heating in improving engine and component life, vehicle driveability, and passenger comfort will not be explicitly considered since these are difficult to quantify in economic terms.

In most of Ontario, block heating can be effective from October to March. During this six-month period, an estimated 150 planned cold-start trips are made. Generalizing from the experience with the 12 test vehicles, we anticipate that on the average, 143 mL of fuel can be saved on each of these trips by block heating for 2 h (Table 12).

At a gasoline price of 42 ¢/L this translates into a saving of 6.0¢ per trip. This gain is made by expanding 1.15 kWh of electricity which at 3.2 ¢/kWh will cost 3.7¢. Thus, the net energy cost saving is 2.3¢ per trip and $3.45/yr -- a very modest net saving. With eight-cylinder engines the savings are larger, viz., 196 mL of gasoline per cold-start which translates into a net annual saving of $6.80 (Table 12).

Thus, to the individual user, the block heater reduces the running costs of a vehicle. The cost of electrical heating is, in most cases, more than compensated for by the cost of gasoline saved. The economics are more favourable in the case of eight-cylinder engines and in those regions where the cost of electricity is lower or the cost of gasoline higher than assumed here.

Further costs of block heating may include the cost of the heater (approx. $12), its installation cost (approx. $25), and the cost of the timer ($10 to $35). The installation of the heater can be carried out readily by owners. The investment in the timer may be partially recouped by various applications in a typical household. Furthermore, a timer will, in general, outlast a heater. Most block heaters in the market place may be subject to corrosion -- especially, the ones whose cases are made of zinc dyecast. Consequently, heaters are not expected to outlast a typical engine. In summary, the minimum fixed cost of an application is $12. Even this modest expenditure cannot be justified by the net energy cost savings. However, when all potential benefits are considered, the block heater becomes a valuable vehicle option whose running costs are paid for by the gasoline savings. It is an option that

provides reliable starting, extended engine, battery and starter life, and passenger comfort.

From a provincial point of view, block heating represents improvements in the balance of payments, industrial activity, and employment. Imports of crude oil are reduced at the expense of higher electricity consumption -- an increasing portion of which will be produced by the utilization of uranium -- an indigenous resource. Most of the block heaters and timers on the marketplace are manufactured in Canada. This trend is expected to continue. Thus, purchase and use of block heaters represents an opportunity for increased industrial activity, employment and net income.

The provincial gasoline conservation potential of block heating is estimated at 55×10^6 L. This estimate is based on the assumption that 2.5 million light-duty vehicles (less than 50% of the present provincial stock) can benefit from block heating for 150 d/yr. It is also estimated that, in the near future, 50% of the stock will have eight-cylinder engines while the other 50% will have four- and six-cylinder engines. The average fuel saving for each vehicle will remain at 143 mL/cold-start.

4/ CONCLUSIONS

The following conclusions may be drawn from the test results documented in this report.

1. Block heating reduces cold-start fuel consumption and net energy costs. Under winter conditions typical of southern Ontario, 2-hour block heating with a 600 W heater decreases gasoline consumption by 100 to 200 mL/cold-start, depending on the engine size. At present, this represents a net energy cost saving of 75¢ to $7.05/yr, viz., the cost of the electricity consumed is more than offset by the gasoline savings.

2. Block heating improves vehicle driveability and reduces cold-start exhaust emissions. With 2 h of block heating, cold-start idle hydrocarbon and carbon monoxide emissions were found to decrease by 44% and 27%, respectively.

3. For economy, block heater application periods should be limited. With a 600 W heater and under typical winter conditions the block temperature approaches steady state levels in approximately 2 h. Further heating will not produce significant fuel economy gains, especially if the vehicle is shielded from wind during the heating period.

4. Further research is needed to accurately quantify the fuel consumption effects of the block heating period, heater rating and wind conditions. The feasibility of limiting the heating period to 1-h without losing the fuel economy gains of block heating under most winter conditions should be investigated, preferably on a chassis dynamometer.

5. Cold-start excess fuel consumption on a short trip (5 to 10 km) under winter conditions amounts to 30 to 50%. On the average, only 20 to 25% of this fuel waste is prevented by block heating.

6. Cold-start fuel consumption was found to correlate with ambient temperature linearly, with $0.81 < r^2 < 0.96$. For the vehicle fleet tested, the sensitivity of fuel consumption to ambient temperature was found to be -0.91 to -3.21 (mL)/(km)(°C) or -0.7 to -1.3 (%)/(°C).

REFERENCES

[1] Ostrouchov, N., "Effect of Cold Weather on Motor Vehicle Emissions and Fuel Economy," SAE Paper No. 780084 (1978).

[2] Ostrouchov, N., "Effect of Cold Weather on Motor Vehicle Emissions and Fuel Consumption -II," SAE Paper No. 780935 (1978).

[3] Hayden, A.C.S., "The Effects of Technology on Automobile Fuel Economy Under Canadian Conditions," SAE Paper No. 780935 (1978).

[4] Eccleston, B.H. and Hurn, R.W., "Ambient Temperature and Trip Length -- Influence on Automotive Fuel Economy and Emissions," SAE Paper No. 780613 (1978).

[5] Pozniak, D.J., "The Exhaust Emission and Fuel Consumption Characteristics of an Engine During Warmup -- A Vehicle Study," SAE Paper No. 800396 (1980).

[6] Marshall, W.F., "Potential for Improving Short-Trip Fuel Economy by Fuel Formulation," SAE Paper No. 790655 (1979).

[7] Everall, P.F. and Northrop, "The Excess Fuel Consumed by Cars When Starting from Cold," RRL Report LR 315, Road Research Laboratory, Ministry of Transport, Crowthorne, Berkshire, U.K. (1970).

[8] Weeks, R., "Fuel Consumption of a Diesel and a Petrol Car," TRRL Report 964, Transport and Road Research Laboratory, Department of the Environment, Department of Transport, Crowthrone, Berkshire.

[9] Pearce, T.C. and Water, M.H.L., "Cold Start Fuel Consumption of a Diesel and Petrol Car," Supplementary Report 636, Transport and Road Research Laboratory, Department of the Environment, Department of Transport, Crowthorne, Berkshire, U.K. (1980).

[10] Odsell, O., "The Use of Electric Engine Heaters -- Influence on Cold Start Fuel Consumption," VTI Report 190, National Swedish Road and Traffic Research Institute, Linkoping, Sweden (1980).

[11] Marshall, W.F. and Eccleston, B.H., "Emissions at Off-Ambient Temperatures," SAE Paper No. 800512 (1980).

[12] Spindt, R.S. and Hutchins, F.P., "The Effect of Ambient Temperature Variation on Emissions and Fuel Economy -- An Interim Report," SAE Paper No. 790228 (1979).

[13] Blackmore, D.R. and Thomas, A., "Fuel Economy of the Gasoline Engine," The MacMillan Press Ltd., London (1977).

[14] Robertson, J.E., "Vehicle Emissions at Low Ambient Temperature and Their Environmental Impact," M. Eng., Proj. Report, Department of Mechanical Engineering, University of Toronto (1977).

[15] Robertson, J.E., "The Impact of Vehicle Emissions on Air Quality at Low Ambient Temperatures," SAE Paper No. 741054 (1974).

[16] Polac, J.C., "Cold Ambient Temperature Effects on Emissions from Light-Duty Motor Vehicles," SAE Paper No. 741051 (1974).

[17] Miles, D.L. and Hornfield, M.F., "The Effect of Ambient Temperature on Exhaust Emissions of Cars with Experimental Emission Controls," SAE Paper No. 741052 (1974).

[18] Ashby, H.A., Stahman, R.C., Eccleston, B.H., and Hurn, R.W. "Vehicle Emissions -- Summer to Winter," SAE Paper No. 741053 (1974).

[19] Environment Canada, "Effect of Cold Weather on Motor Vehicle Emissions," Technology Development Report EPS 4-AP-74-1 (1974).

[20] Environment Canada, "Winter Testing of Automobile Idle Exhaust Emissions in Edmonton, Alberta," Surveillance Report EPS 5-AP-73-14 (1973).

[21] Taylor, G.W., "Automobile Emission Trends in Canada 1960-1985," Environment Canada Report EPS 8-AP-73-1 (1973).

[22] Manos, M.J., Bozek, J.W., and Huls, T.A., "Effect of Laboratory Ambient Conditions on Exhaust Emissions," SAE Paper No. 720124 (1972).

[23] Taylor, C.F., "The Internal-Combustion Engine in Theory and Practice, Volume 1," The MIT Press, U.S.A. (1979).

[24] Kazlauskas, P., Forester, D.D., Kovelon, W.J., Moon, C.L., Ferris, D.R., and Herfurth, W.R., "Coolant Temperature Effects on Engine Life and Performance," SAE Special Publication SP-194 (1961).

[25] Sukala, J.M., and Deckard, M., "Engine Heaters -- First Aid for Cold Weather Starting," SAE Paper No. 740549 (1974).

[26] Sukala, J.M., Deckard, N., and Ritchie, D., "Crankin' Up for Winter," Commercial Car Journal, 62 (1974).

[27] SAE, "Fuel Economy Measurement Road Test Procedure -- Cold Start and Warm-up Fuel Economy -- SAE J1256 JUN80."

[28] Wood, P.S., "The Effect of Specific Vehicle Maintenance Measures on Fuel Consumption," MTC Report DRS-81-01 (1981).

Table 1/ Vehicle Description*

Model Year	Make	Model	Size	Engine Cylinder	Engine Displ. (L)	Trans.	Fuel Consumption Rating (L/100 km) Urban	Hwy.	Comb.
1980	Chevrolet	Citation	M	4	2.5	A3	11.6	6.7	8.8
1980	Pontiac	Parisienne	L	8	5.0	A3	14.6	8.7	11.2
1979	GM	CC20906	Van	8	5.7	A3			
1980	Ford	Fairmont	M	6	3.3	A3	12.2	8.7	10.0
1979	Ford	LTD	L	8	5.8	A3	18.1	10.5	13.8
1981	Dodge	Aries	M	4	2.2	A3	10.8	6.5	8.3

Size Classification

M - Midsize (Passenger and luggage volume: 3.1 to 3.4 m^3)

L - Large (Passenger and luggage volume: greater than 3.4 m^3)

*Two specimens of each model were used in the test program

Table 2/ Vehicle Preparation

Items Checked Before and After Each Test Series

Engine Oil Level

Coolant Level

Transmission Fluid Level

Belts and Hoses

Emission Controls

Choke Operation

Throttle Operation

Pump and Nozzles

Ignition Wires

Brake Drag

Transmission Operation

Tire Pressure and Condition

Engine Tune

Ignition Timing

Idle RPM

Idle CO Emissions

Ignition Point Dwell (if applicable)

Wheel Alignment

Air Cleaner

Fuel Leaks

Manifold Heat Valve

Table 3/ Test Fuel Specifications

Specific Gravity	0.733 at 21°C
Reid Vapour Pressure	63 kPa at 38°C
Boiling Point Range:	
Initial Boiling Point	30°C
10%	49°C
20%	62°C
50%	100°C
90%	168°C
Final Boiling Point	208°C
Recovery	98.5%
Residue	1.0%
Loss	0.5%

TABLE 4/ QUANTITATIVE DESCRIPTION OF DRIVING CYCLE

Table 4(a)/ Total Time Spent in Velocity Ranges:

Speed Range (km/h)	Cruise Time (S)	Total Time (S)	%Time in Cruise	% Time in Speed Range
0-3	4	46	0.5	5.3
3-10	3	60	0.3	7.0
10-20	2	151	0.2	17.5
20-30	5	187	0.6	21.7
30-40	64	417	7.4	48.4
40-50	0	0	0.0	0.0
TOTAL	78	861	9.1	100.0

Number of Stops 22

Table 4(b)/ Total Time Spent in Acceleration Ranges

Accel./Decel. (km/h.s)	Accel. Time (s)	Decel. Time (s)	% Time in Acc. Range	% Time in Dec. Range
0.2-0.6	112	98	13.0	11.4
0.6-1.0	87	101	10.1	11.7
1.0-2.0	62	75	7.2	8.7
2.0-4.0	123	81	14.3	9.4
4.0-8.0	16	28	1.9	3.3
TOTAL	400	383	46.5	44.5

Table 5/ Fuel Consumption - Ambient Temperature Correlations for Cold-Start Tests (Fuel Consumption without Block Heaters)

Vehicle Model	Vehicle No.	FC Correlation*	r^2	T - range (°C)	T_{avg} (°C)
Citation	1	-19.57 T + 1306 (12)**	0.84	-1.1/-17.7	-8.5
	2	-12.37 T + 1261 (13)	0.81	6.9/-14.7	-3.8
	avg.	-15.97 T + 1284			
Parisienne	1	-20.87 T + 1964 (10)	0.82	-0.4/-17.7	-8.3
	2	-20.36 T + 1915 (10)	0.84	-0.3/-19.6	-10.7
	avg.	-20.62 T + 1940			
Van	1	-29.75 T + 3186 (8)	0.88	3.7/-10.6	-2.7
	2	-30.00 T + 3060 (7)	0.88	4.4/-8.0	-0.2
	avg.	-29.88 T + 3123			
Fairmont	1	-8.60 T + 1406 (15)	0.85	6.0/-17.7	-3.2
	2	-9.87 T + 1347 (16)	0.92	4.9/-12.8	-6.6
	avg.	-9.24 T + 1377			
LTD	1	-18.98 T + 2044 (7)	0.91	4.3/-14.7	-7.5
	2	-19.03 T + 2110 (6)	0.92	-1.1/-10.1	-5.5
	avg.	-19.01 T + 2077			
Aries	1	-7.44 T + 1210 (11)	0.88	5.4/-11.7	-0.9
	2	-8.66 T + 1216 (9)	0.85	8.4/-16.0	0.0
	avg.	-8.05 T + 1213			

*FC = fuel consumption over the test cycle in mL
**Number of tests on which correlation is based

Table 6/ Fuel Consumption - Ambient Temperature Correlations for Cold-Start Tests (Fuel Consumption with Block Heater)

Vehicle Model	Vehicle No.	FC Correlation*	r^2	T - range (°C)	T_{avg} (°C)
Citation	1	-12.61 T + 1198 (12)	0.67	-1.1/-17.7	-8.5
	2	-13.27 T + 1294 (13)	0.78	6.9/-14.7	-3.8
	avg.	-12.94 T + 1246			
Parisienne	1	-10.57 T + 1898 (10)	0.89	-0.4/-17.1	-8.3
	2	-15.24 T + 1843 (10)	0.84	-0.3/-19.6	-10.7
	avg.	-12.91 T + 1871			
Van	1	-30.78 T + 2914 (8)	0.92	3.7/-10.6	-2.7
	2	-30.28 T + 3060 (7)	0.96	4.4/ -8.0	-0.2
	avg.	-30.53 T + 2987			
Fairmont	1	-11.27 T + 1304 (15)	0.80	6.0/-17.7	-3.2
	2	- 5.86 T + 1333 (16)	0.90	4.9/-12.8	-6.6
	avg.	- 8.57 T + 1319			
LTD	1	-20.80 T + 1939 (7)	0.96	4.3/-14.7	-7.5
	2	-23.93 T + 1801 (6)	0.92	-1.1/-10.1	-5.5
	avg.	-22.37 T + 1870			
Aries	1	- 7.72 T + 1102 (11)	0.90	5.4/-11.7	-0.9
	2	-10.18 T + 1095 (9)	0.93	8.4/-16.0	0.0
	avg.	- 8.95 T + 1099			

Table 7/ Sensitivity of Fuel Consumption to Ambient Temperature

1/ Without Block Heaters (Baseline Case)

Vehicle	Sensitivity (mL)/(km)(°C)	Sensitivity (%)/(°C)
Citation	-1.81	-1.3
Parisienne	-2.34	-1.1
Van	-3.21	-0.9
Fairmont	-1.05	-0.7
LTD	-2.16	-1.0
Aries	-0.91	-0.7

2/ With Block Heaters (Test Case)

Vehicle	Sensitivity (mL)/(km)(°C)	Sensitivity (%)/(°C)
Citation	-1.47	-1.1
Parisienne	-1.46	-0.7
Van	-3.28	-1.0
Fairmont	-0.97	-0.7
LTD	-2.54	-1.2
Aries	-1.02	-0.9

Table 8/ Cold-Start Excess Fuel Consumption without Block Heaters*

Vehicle	1st Cycle		2nd Cycle		3rd Cycle
	Avg. FC (mL)	Ex. FC (%)	Avg. FC (mL)	Ex. FC (%)	Avg. FC (mL)
1/ Citation	1387	40	1039	5	990
2/ Parisienne	2137	39	1567	2	1541
3/ Van	3174	32	2403	0	2396
4/ Fairmont	1422	30	1106	1	1094
5/ LTD	2199	48	1532	3	1488
6/ Aries	1216	32	910	0	919

*Average fuel consumption data of this table represent arithmetic averages of the experimental measurements provided in the Appendix.

Explanations:
AVG. FC = Average Fuel Consumption
EX. FC = Excess Fuel Consumption

Table 9/ Average Vehicle Fuel Consumption and Fuel Saving in Cold-Start Tests*
(Temperature Range: 0°C to -20°C)

1/ Average Fuel Consumption without Block Heater

Citation	.1444 mL	(16.38 L/100 km)**
Parisienne	.2146 mL	(24.35 L/100 km)
Van.	.3422 mL	(36.80 L/100 km)
Fairmont	.1469 mL	(16.67 L/100 km)
LTD.	.2267 mL	(25.72 L/100 km)
Aries.	.1294 mL	(14.68 L/100 km)

2/ Average Fuel Consumption with Block Heater

Citation	.1375 mL	(15.60 L/100 km)
Parisienne	.2000 mL	(22.69 L/100 km)
Van.	.3292 mL	(35.40 L/100 km)
Fairmont	.1405 mL	(15.94 L/100 km)
LTD.	.2094 mL	(23.76 L/100 km)
Aries.	.1189 mL	(13.49 L/100 km)

3/ Average Fuel Savings with Block Heater

Citation	69 mL	(4.8%)***
Parisienne	146 mL	(6.8%)
Van.	130 mL	(3.8%)
Fairmont	64 mL	(4.4%)
LTD.	173 mL	(7.6%)
Aries.	105 mL	(8.1%)

*Fuel consumption and savings deduced from consumption-temperature correlations in Tables 5 and 6. In some cases, estimates involve extrapolation of experimental data.

**Fuel economy in (L/100 km).

***Percent fuel savings, based on fuel consumption without block heater.

Table 10/ Estimates of Average Total Fuel Consumption and Total Fuel Savings*
(Temperature Range: 0°C to -20°C)

1/ Average Fuel Consumption without Block Heater

Citation	3473 mL	(13.13 L/100 km)
Parisienne	5254 mL	(19.87 L/100 km)
Van	8221 mL	(29.47 L/100 km)
Fairmont	3675 mL	(13.90 L/100 km)
LTD	5287 mL	(19.99 L/100 km)
Aries	3123 mL	(11.81 L/100 km)

2/ Average Fuel Consumption with Block Heater

Citation	3372 mL	(12.75 L/100 km)
Parisienne	5045 mL	(19.08 L/100 km)
Van	8019 mL	(28.74 L/100 km)
Fairmont	3609 mL	(13.65 L/100 km)
LTD	5109 mL	(19.32 L/100 km)
Aries	3020 mL	(11.42 L/100 km)

3/ Average Fuel Savings with Block Heater

Citation	101 mL	(2.9%)
Parisienne	209 mL	(4.0%)
Van	202 mL	(2.5%)
Fairmont	66 mL	(1.8%)
LTD	178 mL	(3.4%)
Aries	103 mL	(3.3%)

*Fuel consumption and savings for the sum of the three test cycles.

Table 11/ Cold-Start Idle Exhaust Emissions
(Averaged over Five Minutes of Idling)

1/ Without Block Heater

Vehicle	$T_{ambient}$ (°C)	(HC) ppm	(CO) %
Citation	-2	320	3.0
Parisienne	-2	741	4.1
Van	-5	671	4.4
Fairmont	-1	410	3.3
LTD	0	515	4.3
Aries	0	346	3.2

2/ With Block Heater

Vehicle	$T_{ambient}$ (°C)	(HC) ppm	(CO) %
Citation	-2	167	1.8
Parisienne	-2	414	3.6
Van	-5	439	3.7
Fairmont	-1	209	1.9
LTD	0	389	3.6
Aries	0	86	1.4

*Parentheses denote concentrations

Table 12/ Fuel and Cost Savings per Cold-Start under Average Winter Conditions in Southern Ontario

Vehicle	Fuel* (mL)	Savings per Cold-Start	
		Fuel Cost (¢)	Net Energy Cost (¢)
1/ Citation	101	4.2	0.5
2/ Parisienne	209	8.8	5.1
3/ Van	202	8.5	4.8
4/ Fairmont	66	2.8	-0.9
5/ LTD	178	7.5	3.8
6/ Aries	103	4.3	0.6

*Fuel savings for the sum of all three cycles.

Assumptions
Cost of gasoline = 43¢/L
Cost of electricity = 3.2¢/kWh

Table B.1/ Fuel Economy Test Data with Block Heaters

Vehicle: 1980 Chevrolet Citation

Test No.	Date	T_{amb} (°C)	Test Vehicle	1st Cycle Test FC (mL)	1st Cycle Std. FC (mL)	2nd Cycle Test FC (mL)	2nd Cycle Std. FC (mL)	3rd Cycle Test FC (mL)	3rd Cycle Std. FC (mL)
1	81 01 12	-17.7	787	1428	1641	977	1160	884	1083
2	13	-8.4	787	1209	1426	920	1116	876	1050
3	14	-10.4	787	1388	1599	984	1139	982	1145
4	15	-8.9	787	1288	1475	965	1044	898	1061
5	16	-10.1	787	1348	1498	989	1171	951	1086
6	19	-4.9	787	1250	1400	939	1011	903	1003
7	20	-3.0	787	1258	1315	930	1000	859	1041
8	21	-7.5	787	1284	1512	967	1101	951	1014
9	22	-1.1	787	1213	1347	895	1065	889	986
10	23	-2.4	787	1273	1357	857	1033	868	1029
11	26	4.3	838	1180	1208	1030	934	1024	912
12	27	-1.2	838	1221	1263	1037	910	937	913
13	28	-7.0	838	1468	1351	1056	911	1037	956
14	29	-9.7	838	1404	1340	1145	948	1041	959
15	30	-14.0	838	1469	1386	1182	1091	1049	957
16	81 02 04	-13.8	838	1442	1487	1120	966	1034	864
17	05	-14.7	838	1524	1471	1179	1068	1035	945
18	06	-6.0	838	1428	1262	1031	986	1136	948
19	10	-4.2	838	1315	1386	1101	1004	1049	955
20	11	5.4	838	1225	1235	1048	914	1034	868
21	12	-16.0	787	1447	1634	1031	1187	947	1175
22	13	-11.7	787	1281	1465	977	1117	939	1086
23	16	2.1	838	1217	1284	1016	1034	985	904
24	17	2.9	838	1304	1187	1095	1175	1102	936
25	19	6.9	838	1278	1141	1020	887	1010	883
Average				1326	1387	1020	1039	977	990
Standard Dev.				100	135	84	93	77	85

Table B.2/ Fuel Economy Test Data with Block Heaters

Vehicle: 1980 Pontiac Parisienne

				1st Cycle		2nd Cycle		3rd Cycle	
Test No.	Date	T_{amb} (°C)	Test Vehicle	Test FC (mL)	Std. FC (mL)	Test FC (mL)	Std. FC (mL)	Test FC (mL)	Std. FC (mL)
1	81 12 11	-8.7	OZY	1950	2162	1563	1607	1505	1487
2	12	-6.1	"	1990	2113	1589	1653	1599	1598
3	15	-7.5	"	1978	2055	1503	1565	1591	1604
4	16	-9.4	"	2022	2201	1573	1674	1554	1554
5	17	-19.6	PAN	2172	2393	1548	1642	1430	1494
6	18	-1.9	"	1914	1981	1579	1626	1488	1492
7	19	-13.8	"	2050	2186	1513	1548	1486	1551
8	22	-7.9	"	2035	2109	1549	1641	1457	1492
9	81 01 05	-14.3	"	2084	2184	1542	1622	1420	1539
10	06	-6.2	"	1865	1966	1403	1501	1420	1381
11	07	-12.9	"	2041	2289	1503	1626	1518	1633
12	08	-18.8	"	2091	2311	1570	1613	1550	1660
13	09	-10.8	"	1979	2026	1542	1488	1512	1495
14	12	-17.7	OZY	2082	2360	1673	1612	1595	1605
15	13	-12.0	"	2018	2173	1555	1467	1553	1564
16	14	-10.4	"	2009	2082	1511	1485	1545	1549
17	15	-8.9	"	1950	2161	1501	1480	1514	1533
18	19	-0.4	"	1902	1986	1412	1453	1550	1541
19	20	-2.0	"	1907	2022	1434	1478	1495	1534
20	22	-0.3	PAN	1827	1988	1524	1564	1540	1523
Average				1993	2137	1529	1567	1516	1541
Standard Dev.				85	129	63	73	55	62

Table B.3/ Fuel Economy Test Data with Block Heaters

Vehicle: 1980 Chevrolet Van

				1st Cycle		2nd Cycle		3rd Cycle	
Test No.	Date	T_{amb} (°C)	Test Vehicle	Test FC (mL)	Std. FC (mL)	Test FC (mL)	Std. FC (mL)	Test FC (mL)	Std. FC (mL)
1	80 02 20	4.4	1631	2857	2966	2376	2397	2398	2419
2	23	3.7	1632	2806	3049	2372	2421	2475	2476
3	24	2.0	1631	2883	2989	2355	2386	2351	2398
4	25	0.5	1632	2859	3165	2368	2397	2401	2405
5	26	-1.6	1631	3007	3093	2328	2377	2464	2476
6	81 03 03	-6.9	1632	3108	3303	2340	2386	2397	2433
7	04	-0.9	1631	3019	3115	2367	2409	2296	2301
8	05	-2.0	1632	2993	3325	2372	2420	2398	2457
9	10	1.9	1631	2894	2917	2371	2374	2209	2269
10	11	0.0	1632	2996	3162	2392	2408	2281	2357
11	12	0.8	1631	3048	3080	2355	2411	2269	2319
12	13	-0.1	1632	2869	3235	2381	2397	2330	2352
13	16	-10.6	1632	3264	3542	2344	2422	2411	2430
14	17	-8.0	1631	3217	3302	2309	2404	2405	2456
15	18	-6.5	1632	3090	3371	2408	2435	2382	2395
Average				2994	3174	2363	2403	2364	2396
Standard Dev.				136	172	25	18	74	64

Table B.4/ Fuel Economy Test Data with Block Heaters

Vehicle: 1980 Ford Fairmont

Test No.	Date	T_{amb} (°C)	Test Vehicle	1st Cycle Test FC (mL)	1st Cycle Std. FC (mL)	2nd Cycle Test FC (mL)	2nd Cycle Std. FC (mL)	3rd Cycle Test FC (mL)	3rd Cycle Std. FC (mL)
1	80 11 17	-1.5	235	1340	1331	1086	1105	1111	1086
2	19	-0.1	235	1329	1383	1111	1074	1138	1049
3	20	2.2	235	1309	1320	1104	1097	1068	1054
4	25	-1.5	271	1364	1444	1107	1107	1090	1083
5	26	-0.6	271	1280	1404	1074	1075	1055	1054
6	27	1.3	271	1275	1400	1071	1059	1063	1097
7	80 12 01	4.4	235	1308	1293	1109	1038	1094	1011
8	03	-7.6	235	1394	1412	1145	1121	1147	1126
9	04	-8.5	235	1385	1408	1137	1118	1115	1084
10	08	6.0	235	1308	1313	1172	1138	1198	1082
11	09	1.0	271	1297	1387	1055	1147	1108	1118
12	10	-0.6	271	1351	1440	1084	1136	1055	1105
13	11	-7.0	271	1368	1443	1083	1129	1074	1112
14	15	-4.8	271	1365	1445	1091	1094	1113	1112
15	16	-6.8	271	1413	1487	1048	1142	1056	1101
16	17	-11.9	235	1398	1491	1122	1120	1072	1133
17	18	-1.8	235	1340	1359	1148	1087	1021	1070
18	81 01 05	-14.0	235	1431	1479	1157	1167	1148	1122
19	07	-13.0	235	1363	1499	1152	1170	1183	1210
20	08	-16.0	235	1433	1509	1136	1095	1133	1113
21	09	-10.0	235	1398	1406	1109	1071	1073	1047
22	12	-17.7	235	1443	1528	1107	1167	1100	1060
23	19	-0.6	271	1261	1418	1048	1052	1039	1083
24	20	-2.0	271	1324	1415	1136	1145	1107	1142
25	27	-1.2	271	1291	1388	1093	1080	1083	1115
26	28	-5.0	235	1360	1402	1122	1128	1112	1111
27	29	-7.7	271	1393	1457	1061	1077	1087	1121
28	81 02 03	-12.8	271	1438	1518	1138	1089	1036	1006
29	04	-11.7	235	1404	1470	1156	1193	1113	1168
30	05	-9.2	271	1414	1491	1130	1135	1109	1100
31	17	4.9	271	1268	1357	1048	1077	1069	1080
Average				1356	1422	1108	1111	1096	1095
Standard Dev.				54	63	36	38	41	40

Table B.5/ Fuel Economy Test Data with Block Heaters

Vehicle: 1980 Ford Ltd

Test No.	Date	T_{amb} (°C)	Test Vehicle	1st Cycle Test FC (mL)	1st Cycle Std. FC (mL)	2nd Cycle Test FC (mL)	2nd Cycle Std. FC (mL)	3rd Cycle Test FC (mL)	3rd Cycle Std. FC (mL)
1	81 01 16	-10.1	OSX	2078	2281	1614	1689	1553	1638
2	20	-3.0	"	1865	2153	1404	1509	1375	1479
3	21	-7.5	"	1939	2292	1446	1569	1401	1490
4	22	-1.1	"	1829	2126	1453	1498	1345	1428
5	23	-2.4	"	1880	2161	1503	1526	1397	1469
6	26	4.3	OZO	1831	1951	1486	1462	1431	1439
7	27	-1.2	"	1985	2075	1538	1460	1492	1471
8	28	-7.0	"	2065	2131	1488	1453	1492	1409
9	81 02 03	-14.2	"	2201	2375	1670	1572	1619	1524
10	04	-13.8	"	2280	2252	1608	1548	1608	1497
11	05	-14.7	"	2220	2309	1559	1529	1610	1496
12	06	-6.0	"	2088	2210	1581	1518	1595	1477
13	07	-8.8	OSX	2004	2271	1521	1580	1400	1525
Average				2020	2199	1529	1532	1486	1488
Standard Dev.				151	114	76	64	101	57

Table B.6/ Fuel Economy Test Data with Block Heaters

Vehicle: 1980 Dodge Aries

Test No.	Date	T_{amb} (°C)	Test Vehicle	1st Cycle Test FC (mL)	1st Cycle Std. FC (mL)	2nd Cycle Test FC (mL)	2nd Cycle Std. FC (mL)	3rd Cycle Test FC (mL)	3rd Cycle Std. FC (mL)
1	81 02 09	-8.8	190	1165	1273	921	965	937	911
2	10	-4.2	110	1127	1228	926	944	924	971
3	11	5.4	190	1066	1144	952	926	941	970
4	12	-16.0	110	1252	1371	981	982	948	1003
5	13	-11.7	190	1191	1286	963	935	988	975
6	16	2.1	110	1060	1188	872	889	876	988
7	17	2.9	190	1061	1218	944	921	924	905
8	19	6.9	110	1045	1193	909	943	840	943
9	20	4.4	190	1063	1181	835	888	888	846
10	23	8.4	110	980	1139	876	816	820	889
11	24	2.2	110	1037	1207	836	832	816	862
12	25	0.4	110	1075	1164	812	823	828	835
13	27	-2.1	190	1130	1236	923	921	912	911
14	81 03 02	-1.4	110	1138	1253	906	959	910	950
15	03	-3.6	190	1141	1256	940	936	924	906
16	04	1.8	110	1102	1198	947	926	892	933
17	06	-3.5	190	1125	1239	935	903	948	895
18	10	2.6	190	1055	1179	982	900	958	935
19	11	0.5	190	1108	1192	997	915	984	851
20	12	4.5	190	1090	1181	928	871	978	909
Average				1101	1216	919	910	912	919
Standard Dev.				61	54	51	46	53	48

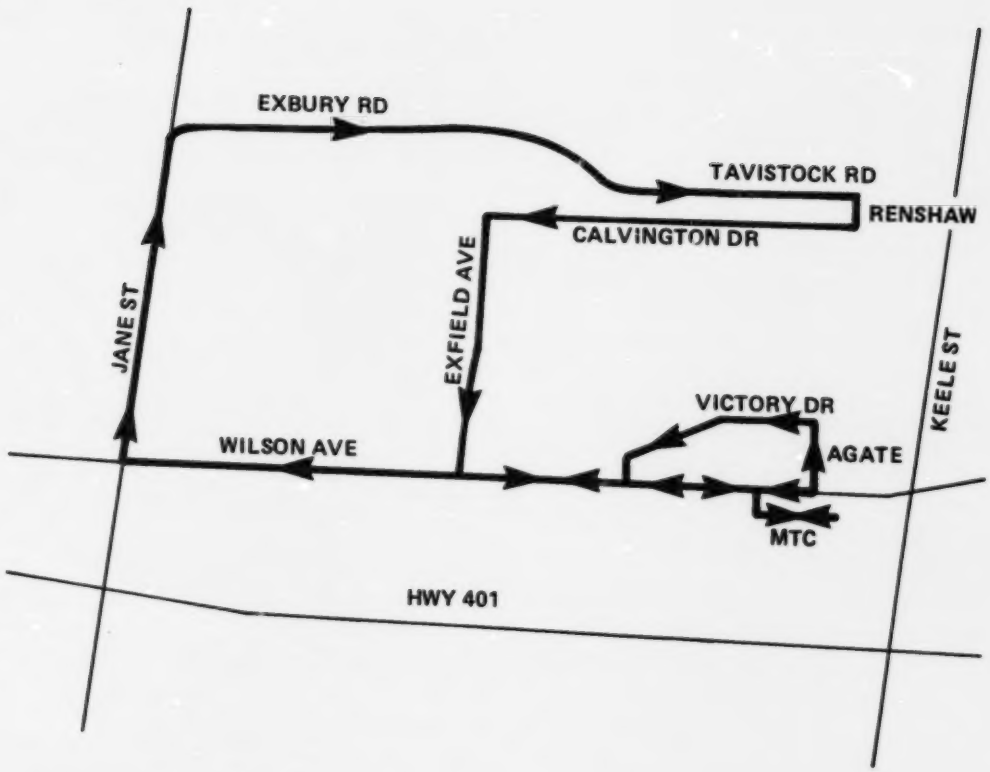

Figure 1/ The Test Route

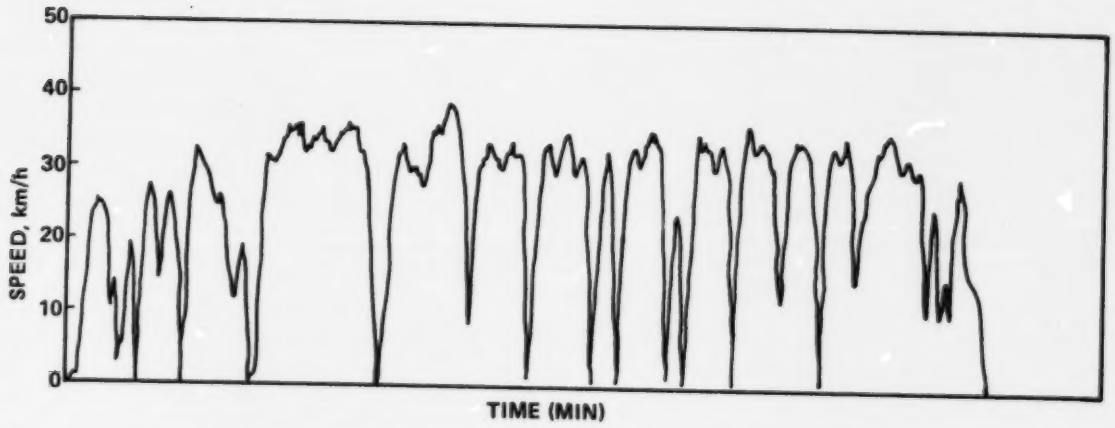

Figure 2/ The Driving Cycle

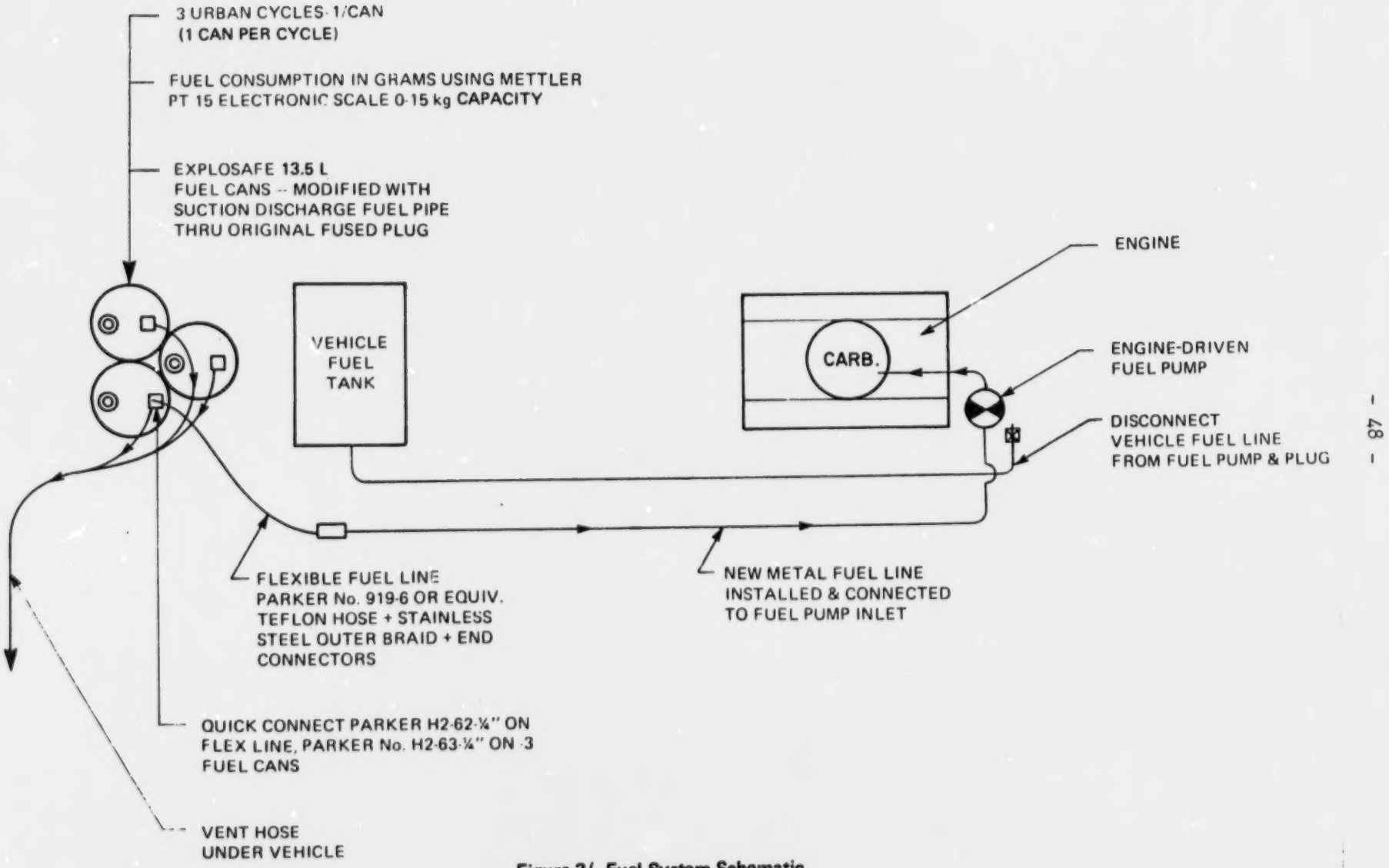

Figure 3/ Fuel System Schematic

FIGURES 4 to 15

Title: Cold Start Fuel Consumption as a Function of Ambient Temperature -- Experimental Data and Linear Least Squares Correlations

Explanations: The data obtained with each vehicle model is presented in two consecutive figures. Each figure involves a specific vehicle combination, i.e., test and standard vehicle The fuel consumption of the test vehicle (block heated vehicle) is represented by "▲" while that of the standard vehicle is represented by "■".

Solid lines represent least sqares fits to the experimental data. Dashed lines represent 90% confidence envelopes. The association of least squares lines and confidence envelopes in indicated by the integers one and two.

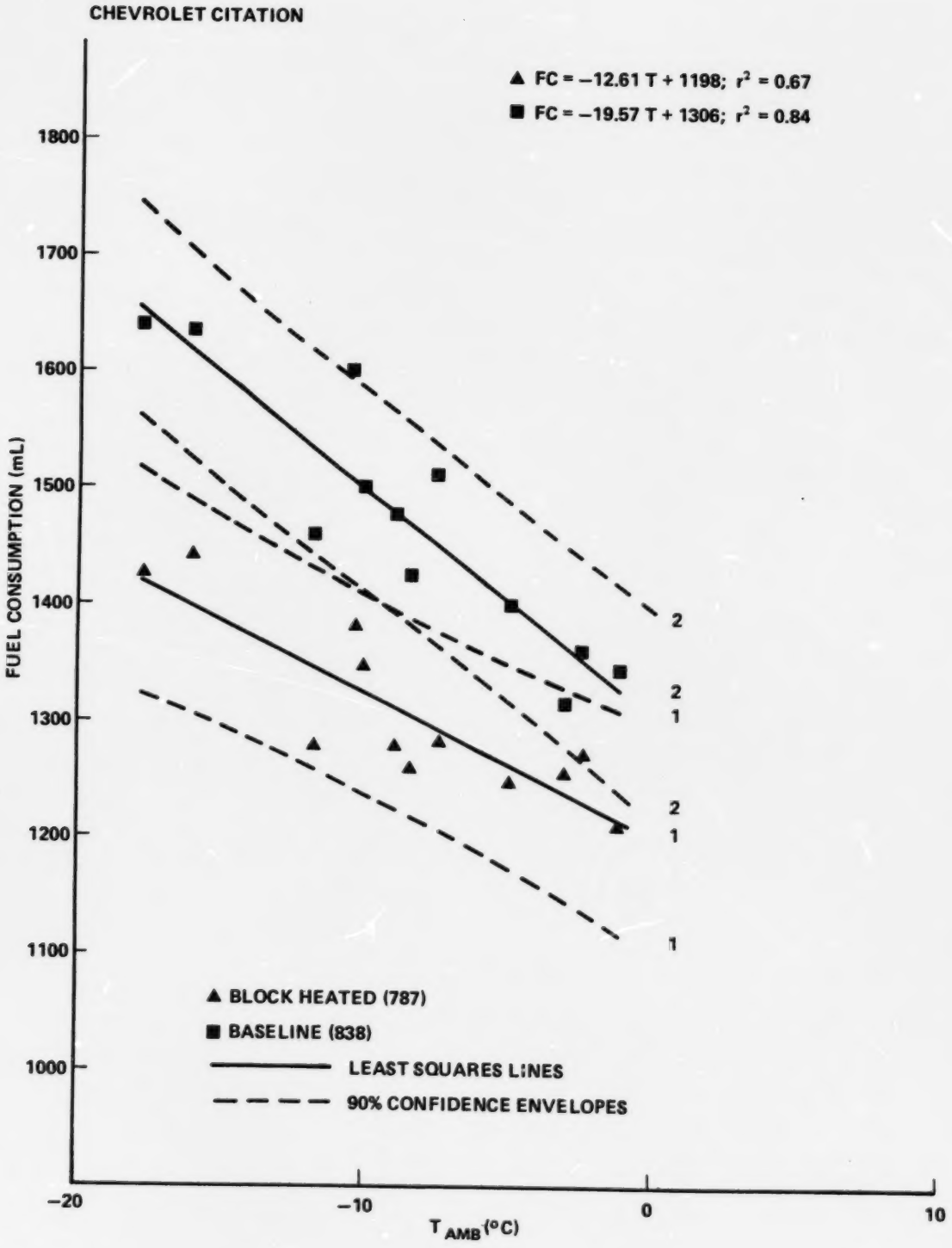
CHEVROLET CITATION
▲ FC = −12.61 T + 1198; r² = 0.67
■ FC = −19.57 T + 1306; r² = 0.84
FUEL CONSUMPTION (mL)
1800
1700
1600
1500
1400
1300
1200
1100
1000
2
2
1
2
1
1
▲ BLOCK HEATED (787)
■ BASELINE (838)
LEAST SQUARES LINES
90% CONFIDENCE ENVELOPES
−20
−10
0
10
T AMB (°C)

Figure 4

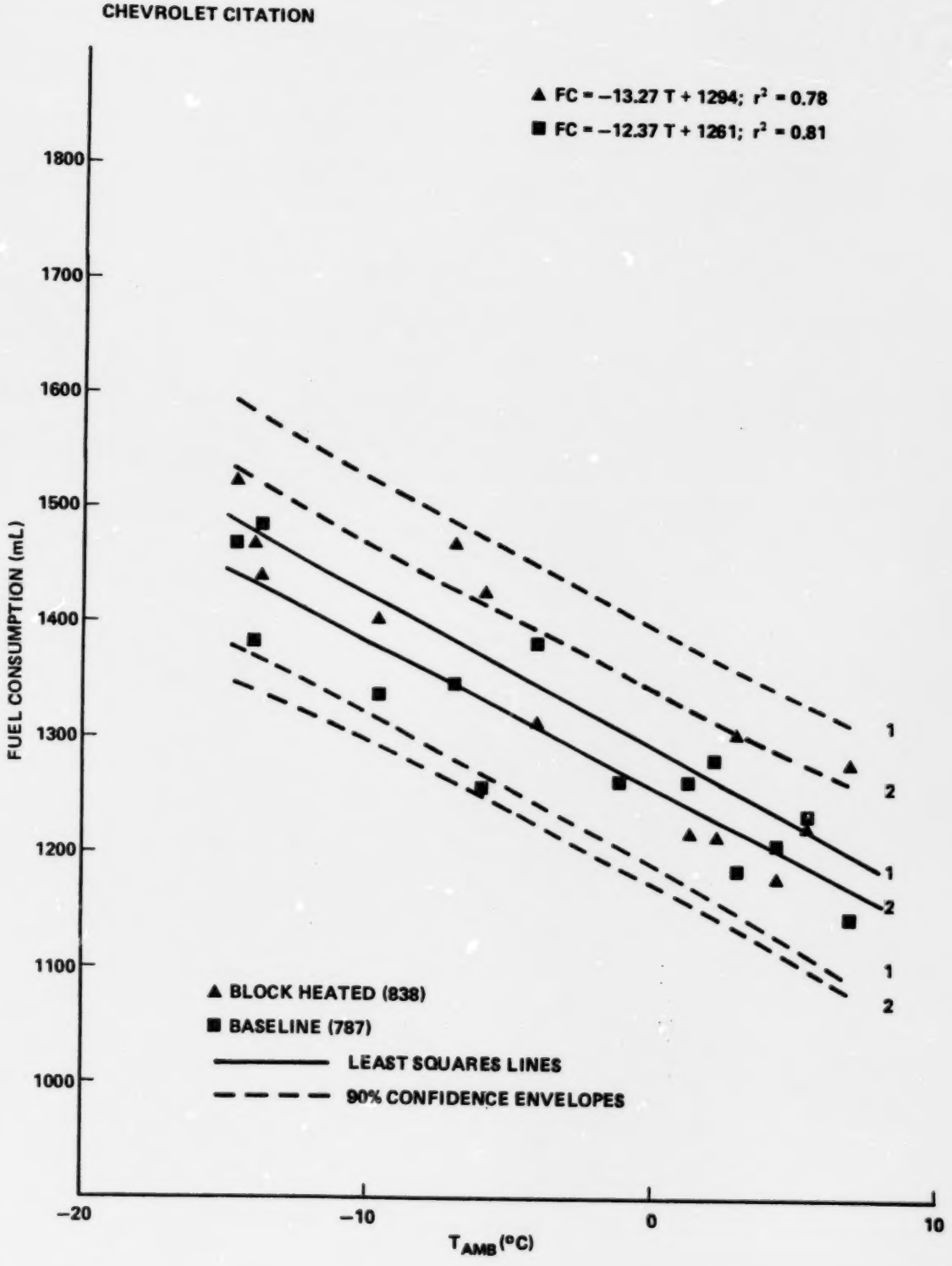
CHEVROLET CITATION
▲ FC = −13.27 T + 1294; r² = 0.78
■ FC = −12.37 T + 1261; r² = 0.81
FUEL CONSUMPTION (mL)
1800
1700
1600
1500
1400
1300
1200
1100
1000
−20
−10
0
10
T_AMB (°C)
1
2
1
2
1
2
▲ BLOCK HEATED (838)
■ BASELINE (787)
LEAST SQUARES LINES
90% CONFIDENCE ENVELOPES

Figure 5

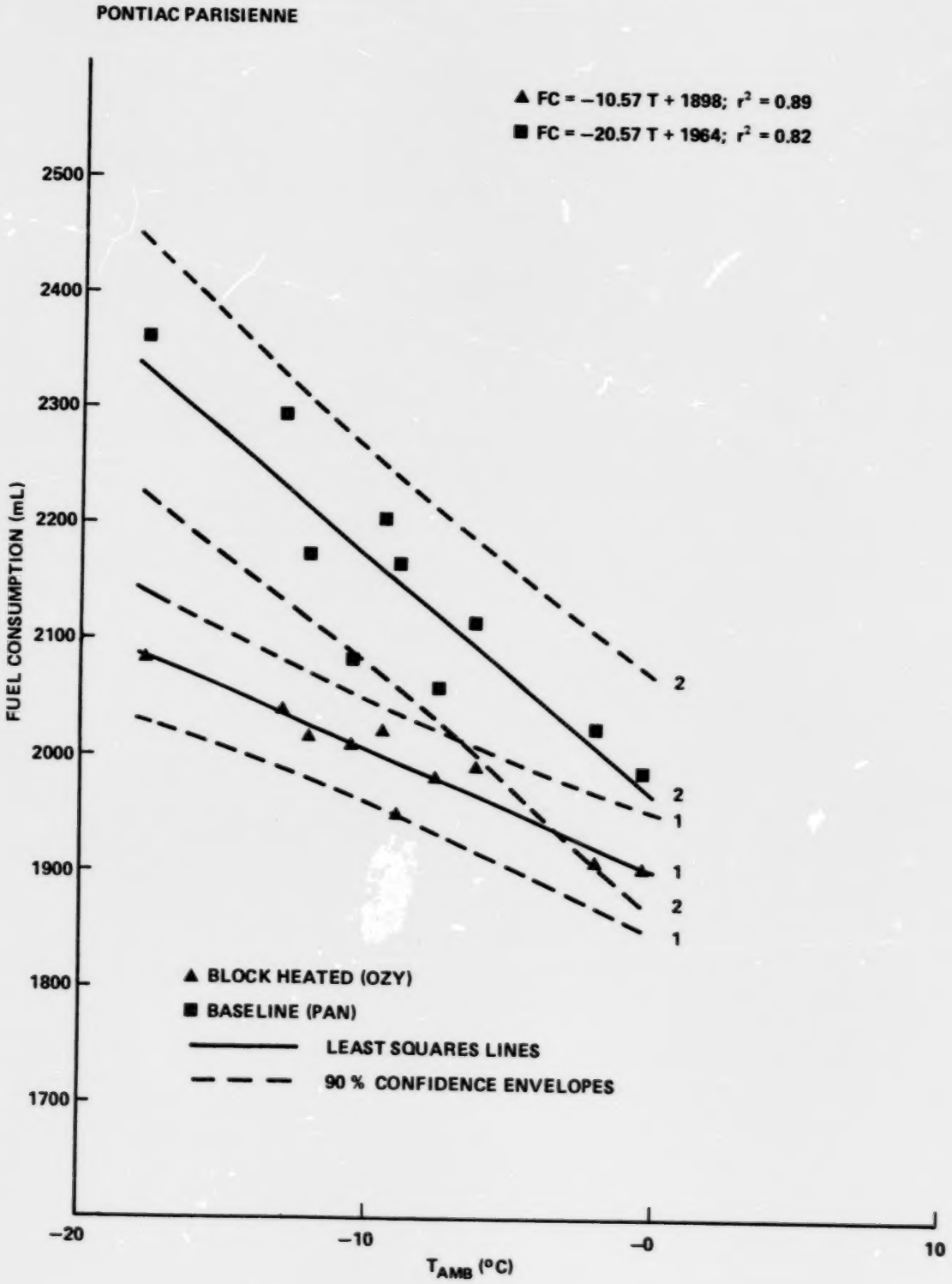
PONTIAC PARISIENNE
▲ FC = −10.57 T + 1898; r² = 0.89
■ FC = −20.57 T + 1964; r² = 0.82
FUEL CONSUMPTION (mL)
2500
2400
2300
2200
2100
2000
1900
1800
1700
2
2
1
1
2
1
▲ BLOCK HEATED (OZY)
■ BASELINE (PAN)
LEAST SQUARES LINES
90 % CONFIDENCE ENVELOPES
−20
−10
−0
10
T_AMB (°C)

Figure 6

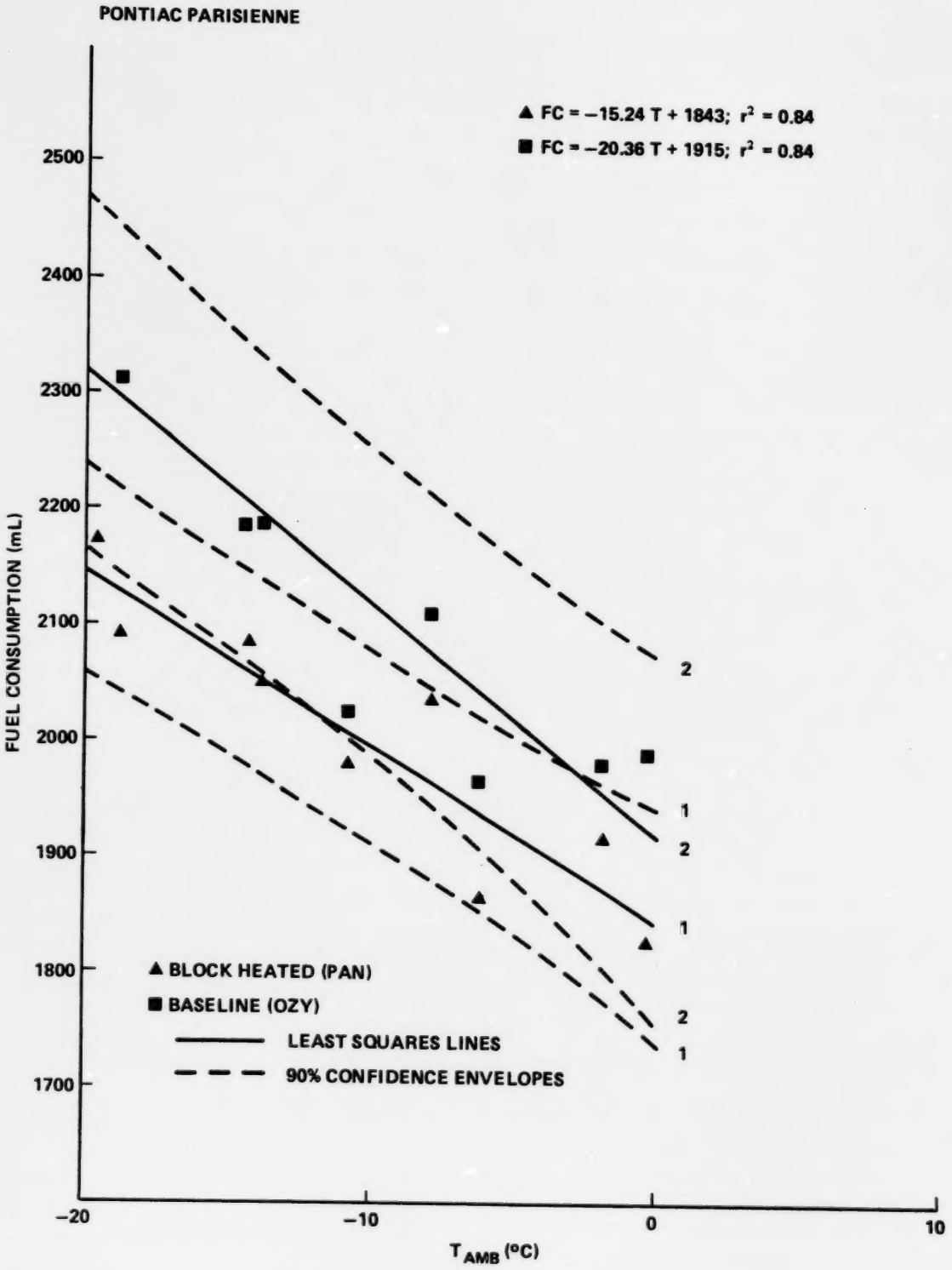
PONTIAC PARISIENNE
▲ FC = −15.24 T + 1843; r² = 0.84
■ FC = −20.36 T + 1915; r² = 0.84
FUEL CONSUMPTION (mL)
2500
2400
2300
2200
2100
2000
1900
1800
1700
−20
−10
0
10
T AMB (°C)
2
1
2
1
2
1
▲ BLOCK HEATED (PAN)
■ BASELINE (OZY)
LEAST SQUARES LINES
90% CONFIDENCE ENVELOPES

Figure 7

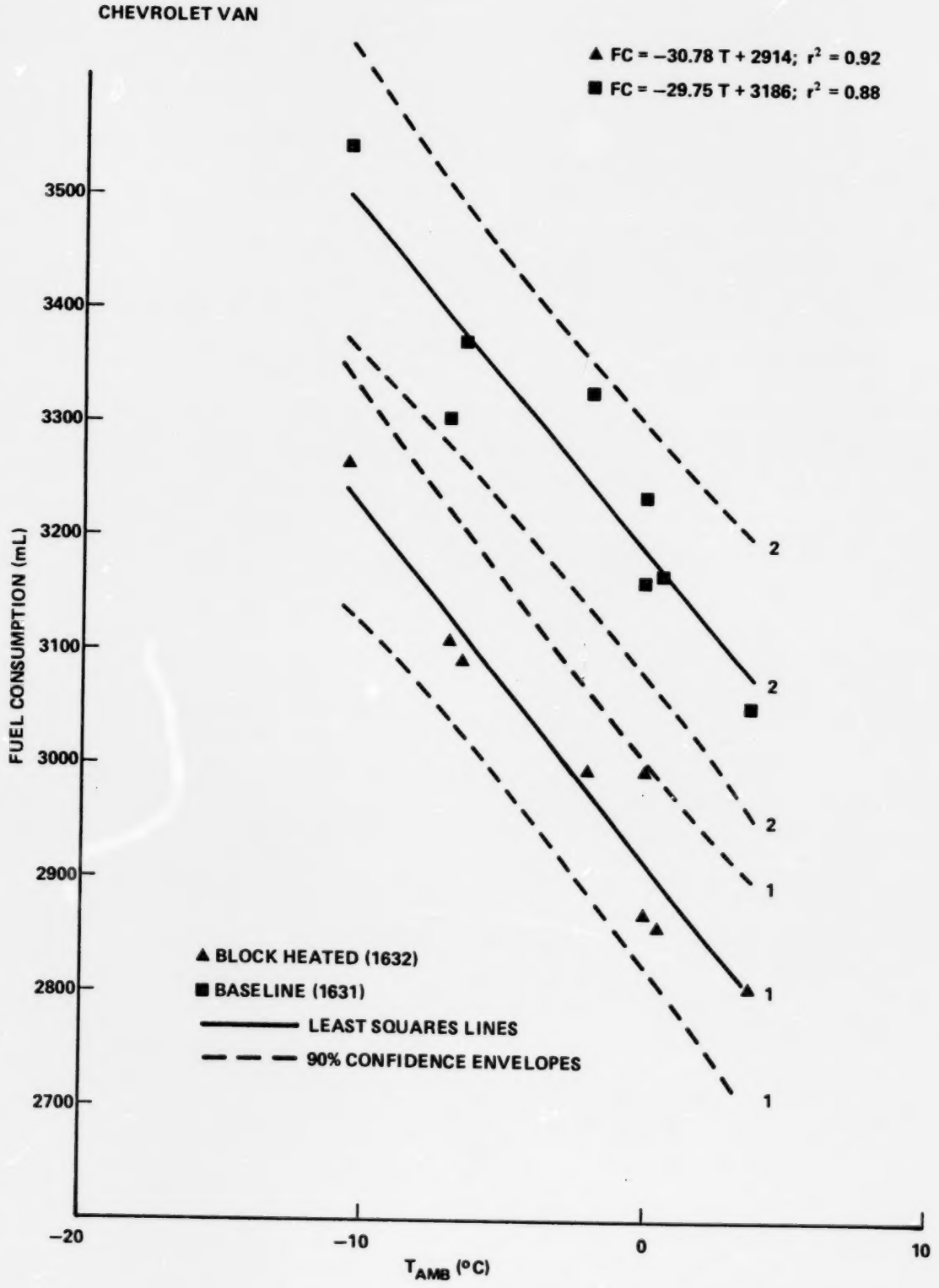
CHEVROLET VAN
▲ FC = −30.78 T + 2914; r² = 0.92
■ FC = −29.75 T + 3186; r² = 0.88
FUEL CONSUMPTION (mL)
3500
3400
3300
3200
3100
3000
2900
2800
2700
2
2
2
1
1
1
▲ BLOCK HEATED (1632)
■ BASELINE (1631)
LEAST SQUARES LINES
90% CONFIDENCE ENVELOPES
−20
−10
0
10
T_AMB (°C)

Figure 8

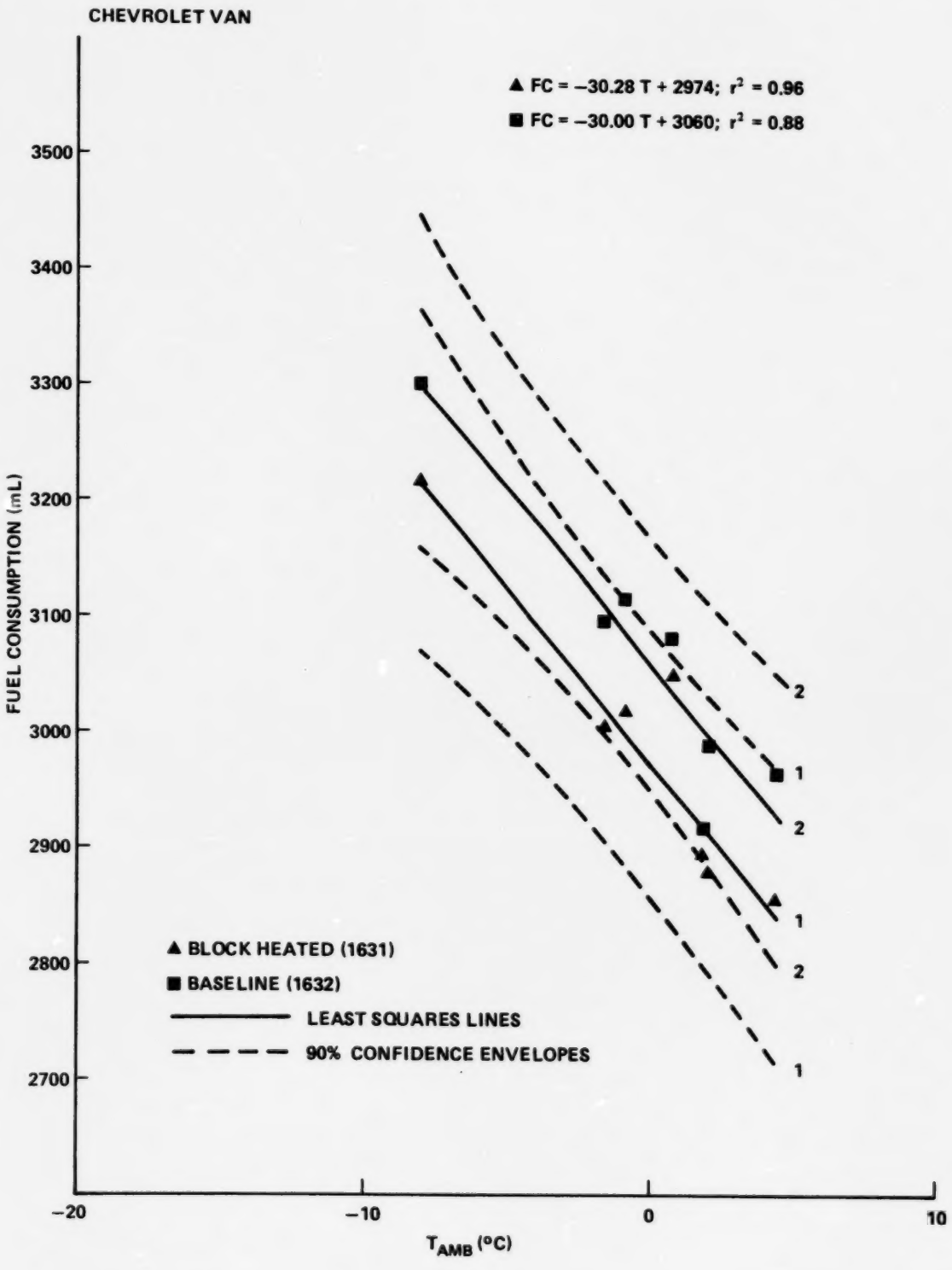
CHEVROLET VAN
▲ FC = −30.28 T + 2974; r² = 0.96
■ FC = −30.00 T + 3060; r² = 0.88
FUEL CONSUMPTION (mL)
3500
3400
3300
3200
3100
3000
2900
2800
2700
−20
−10
0
10
T_AMB (°C)
2
1
2
1
2
1
▲ BLOCK HEATED (1631)
■ BASELINE (1632)
LEAST SQUARES LINES
90% CONFIDENCE ENVELOPES

Figure 9

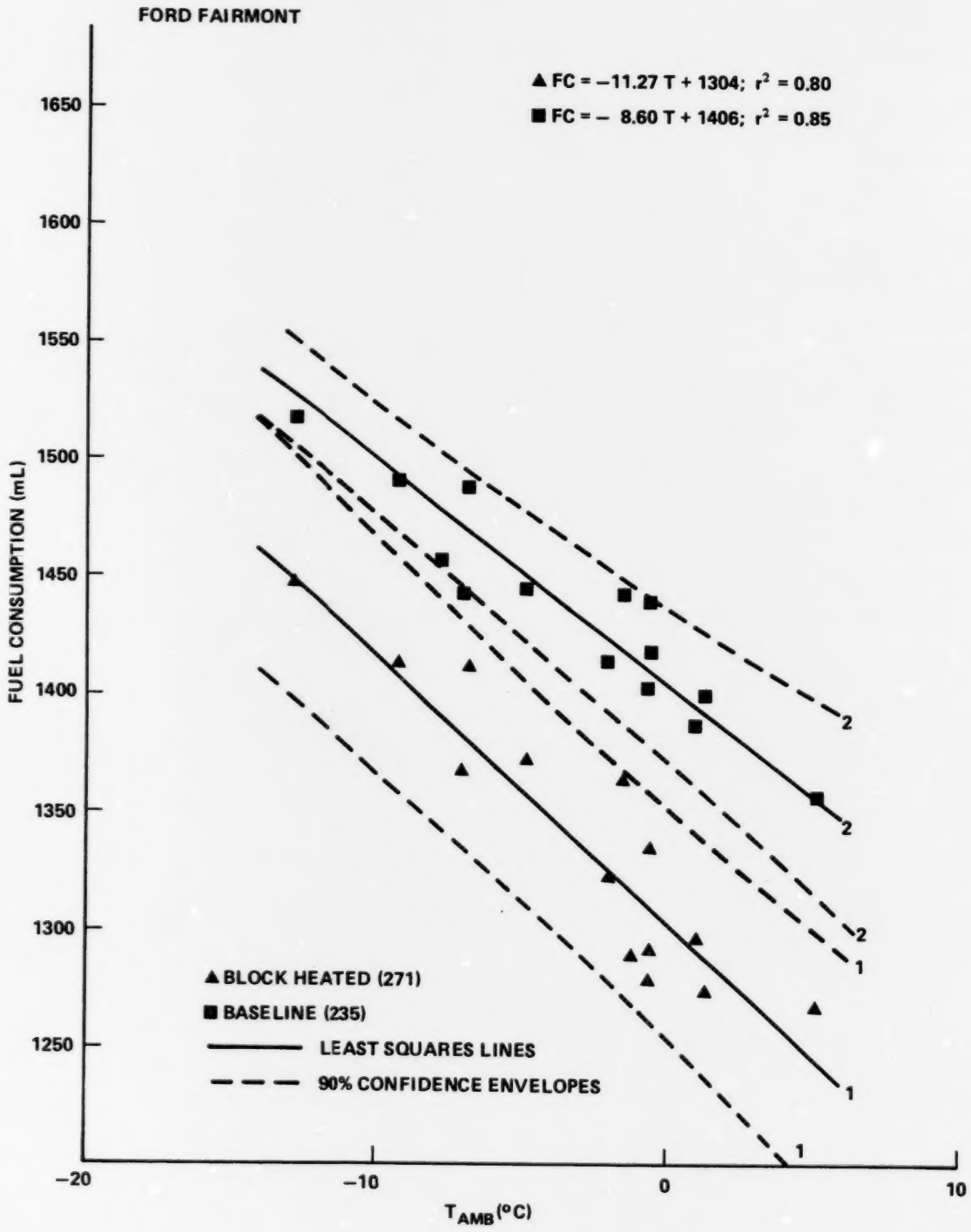
FORD FAIRMONT
▲ FC = −11.27 T + 1304; r² = 0.80
■ FC = − 8.60 T + 1406; r² = 0.85
FUEL CONSUMPTION (mL)
1650
1600
1550
1500
1450
1400
1350
1300
1250
−20
−10
0
10
T_AMB (°C)
2
2
2
1
1
1
▲ BLOCK HEATED (271)
■ BASELINE (235)
LEAST SQUARES LINES
90% CONFIDENCE ENVELOPES

Figure 10

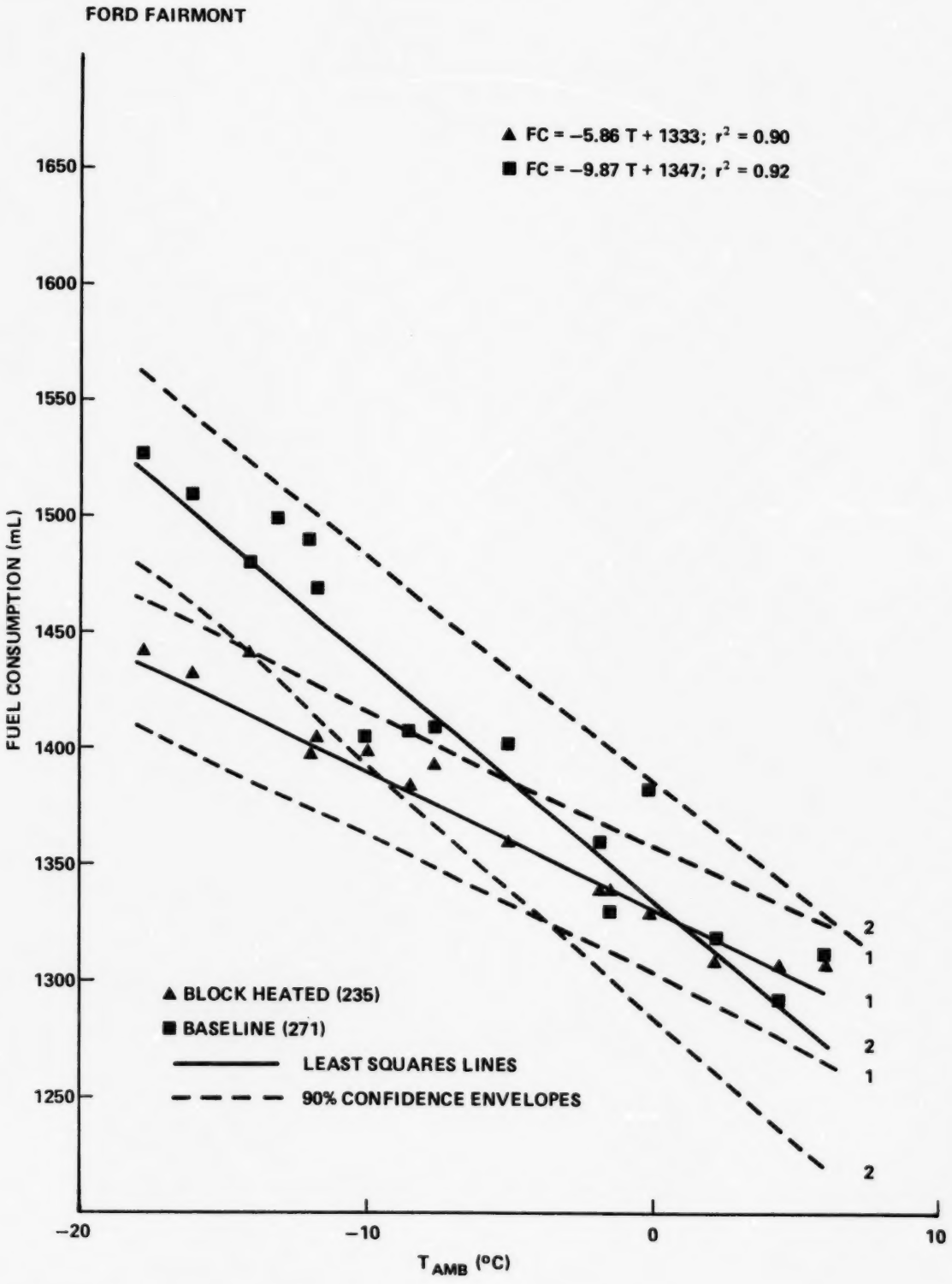
FORD FAIRMONT
▲ FC = –5.86 T + 1333; r² = 0.90
■ FC = –9.87 T + 1347; r² = 0.92
FUEL CONSUMPTION (mL)
1650
1600
1550
1500
1450
1400
1350
1300
1250
–20
–10
0
10
T AMB (°C)
▲ BLOCK HEATED (235)
■ BASELINE (271)
LEAST SQUARES LINES
90% CONFIDENCE ENVELOPES
2
1
1
2
1
2

Figure 11

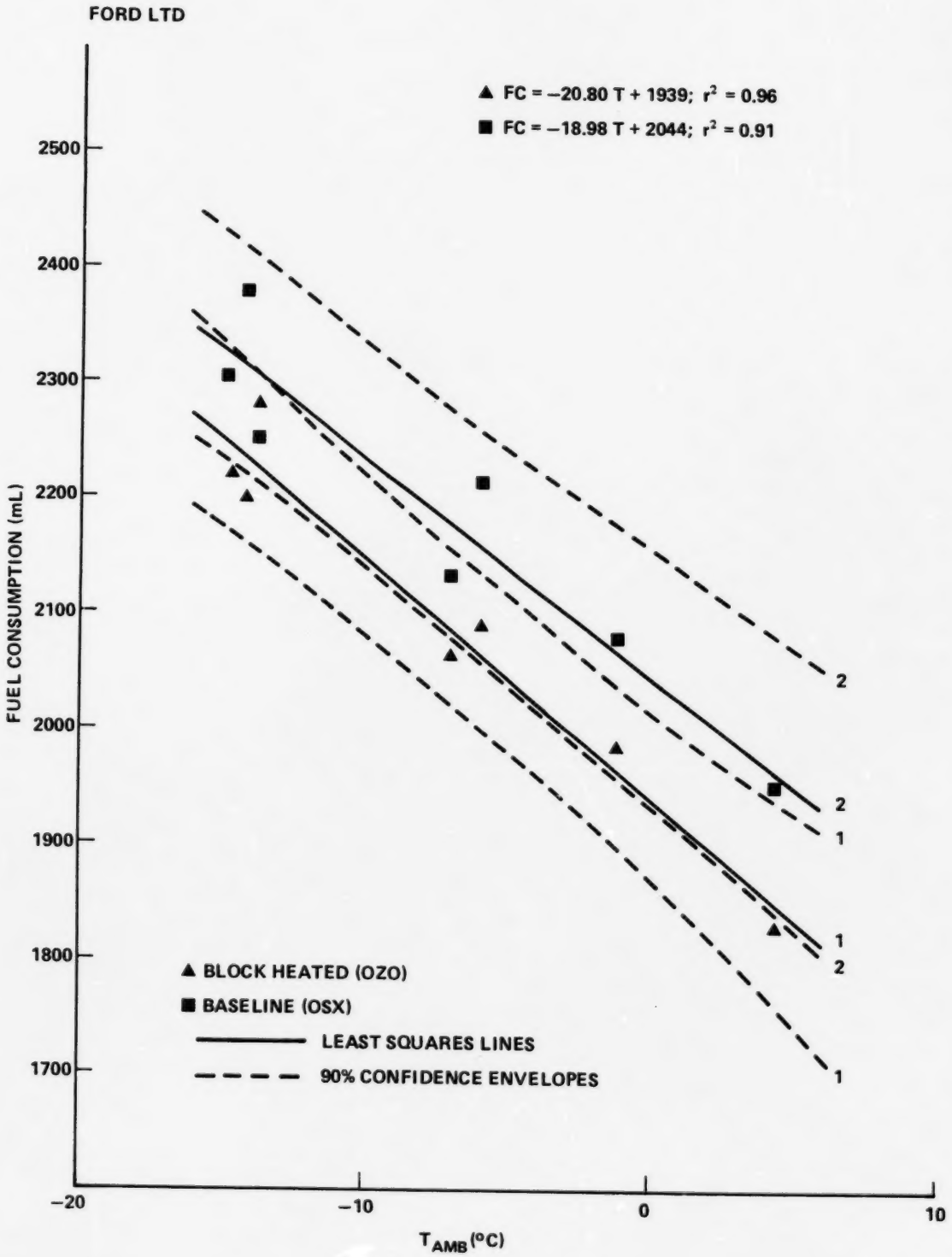
FORD LTD
▲ FC = −20.80 T + 1939; r² = 0.96
■ FC = −18.98 T + 2044; r² = 0.91
FUEL CONSUMPTION (mL)
2500
2400
2300
2200
2100
2000
1900
1800
1700
2
2
1
1
2
1
▲ BLOCK HEATED (OZO)
■ BASELINE (OSX)
LEAST SQUARES LINES
90% CONFIDENCE ENVELOPES
−20
−10
0
10
T_AMB (°C)

Figure 12

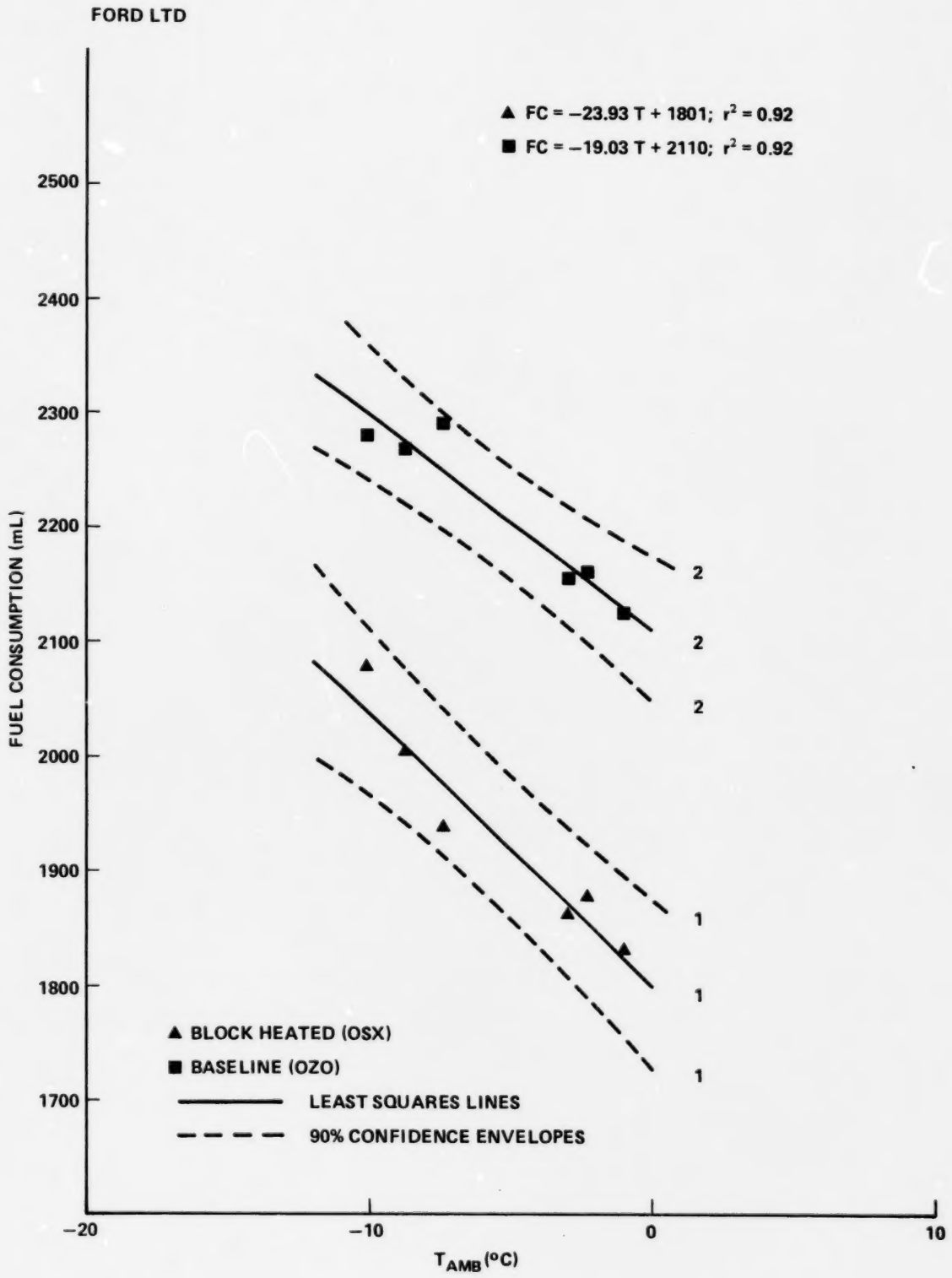
FORD LTD
▲ FC = −23.93 T + 1801; r² = 0.92
■ FC = −19.03 T + 2110; r² = 0.92
FUEL CONSUMPTION (mL)
2500
2400
2300
2200
2100
2000
1900
1800
1700
2
2
2
1
1
1
▲ BLOCK HEATED (OSX)
■ BASELINE (OZO)
LEAST SQUARES LINES
90% CONFIDENCE ENVELOPES
−20
−10
0
10
T_AMB (°C)

Figure 13

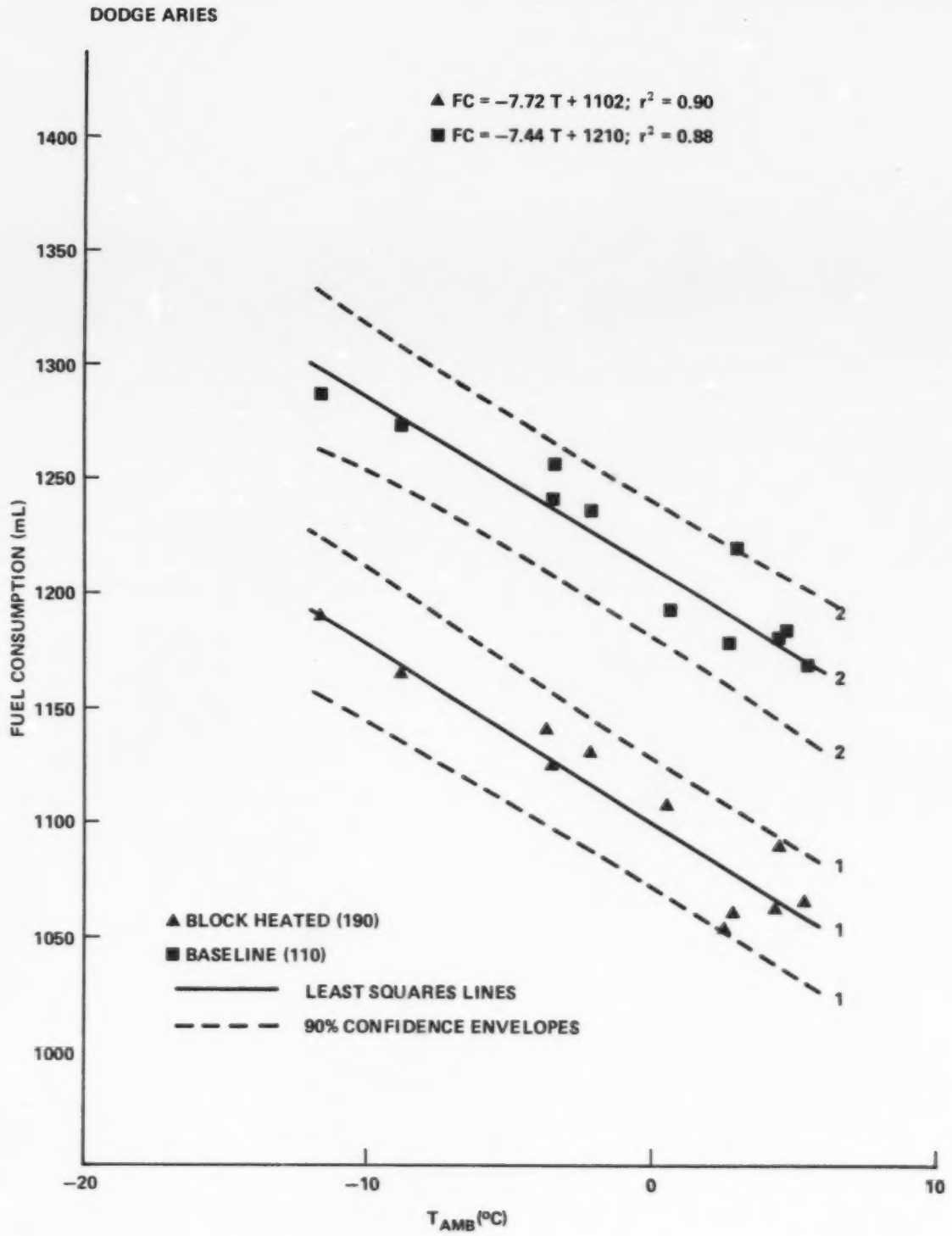
DODGE ARIES
▲ FC = –7.72 T + 1102; r² = 0.90
■ FC = –7.44 T + 1210; r² = 0.88
FUEL CONSUMPTION (mL)
1400
1350
1300
1250
1200
1150
1100
1050
1000
2
2
2
1
1
1
▲ BLOCK HEATED (190)
■ BASELINE (110)
LEAST SQUARES LINES
90% CONFIDENCE ENVELOPES
–20
–10
0
10
T_AMB (°C)

Figure 14

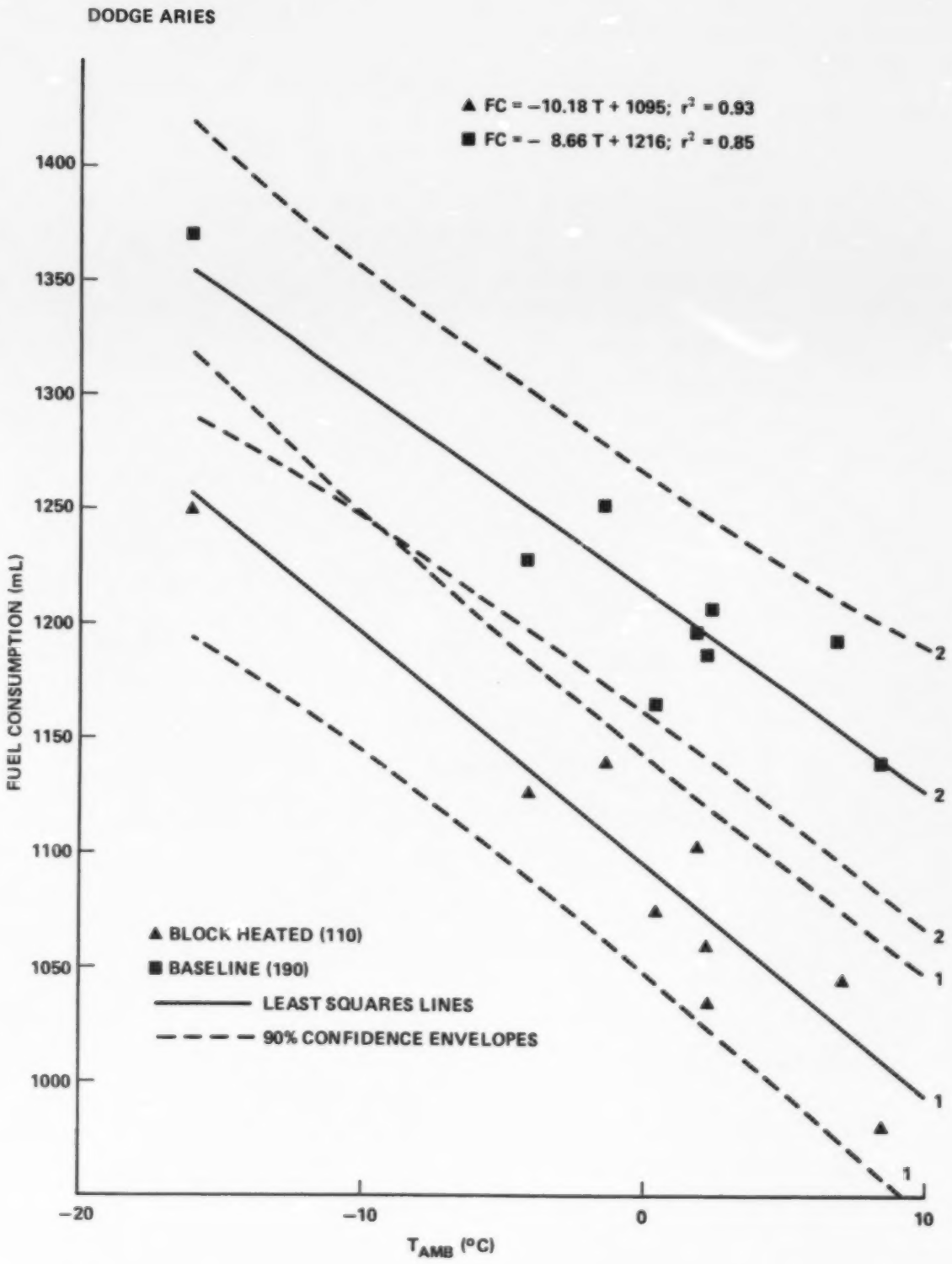
DODGE ARIES
▲ FC = −10.18 T + 1095; r² = 0.93
■ FC = − 8.66 T + 1216; r² = 0.85
FUEL CONSUMPTION (mL)
1400
1350
1300
1250
1200
1150
1100
1050
1000
−20
−10
0
10
T_AMB (°C)
2
2
2
1
1
1
▲ BLOCK HEATED (110)
■ BASELINE (190)
LEAST SQUARES LINES
90% CONFIDENCE ENVELOPES

Figure 15

FIGURES 16 to 21

Title: Block Temperature Response to Heating

Explanations: Temperature-time profiles of cold-soaked block under heater application. Time zero designates beginning of block heating. For each vehicle model tested two representative profiles are provided -- the upper profile represents the block-heated side of the engine while the lower profile represents the opposite side.

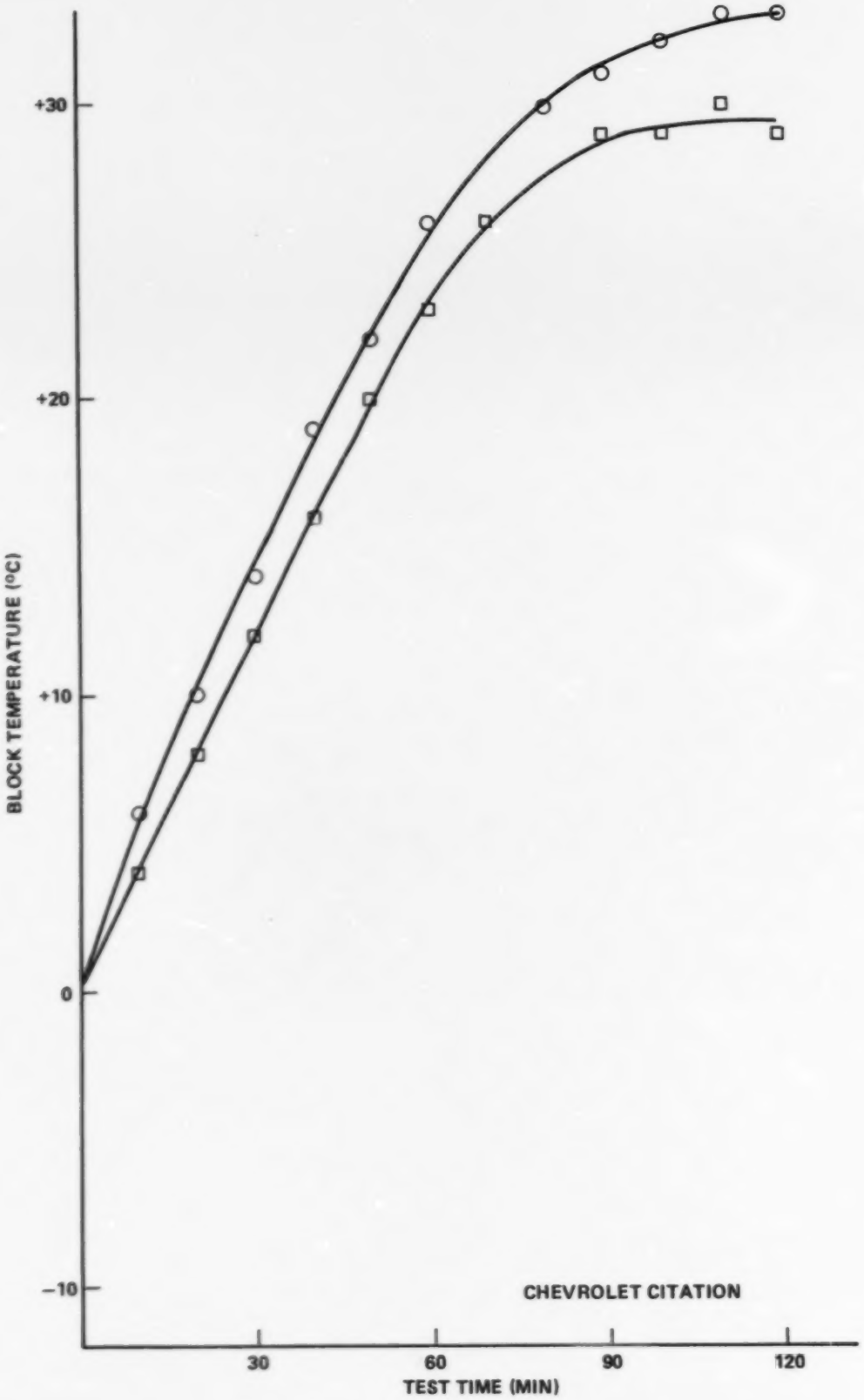
+30
+20
+10
0
−10
BLOCK TEMPERATURE (°C)
CHEVROLET CITATION
30
60
90
120
TEST TIME (MIN)

Figure 16

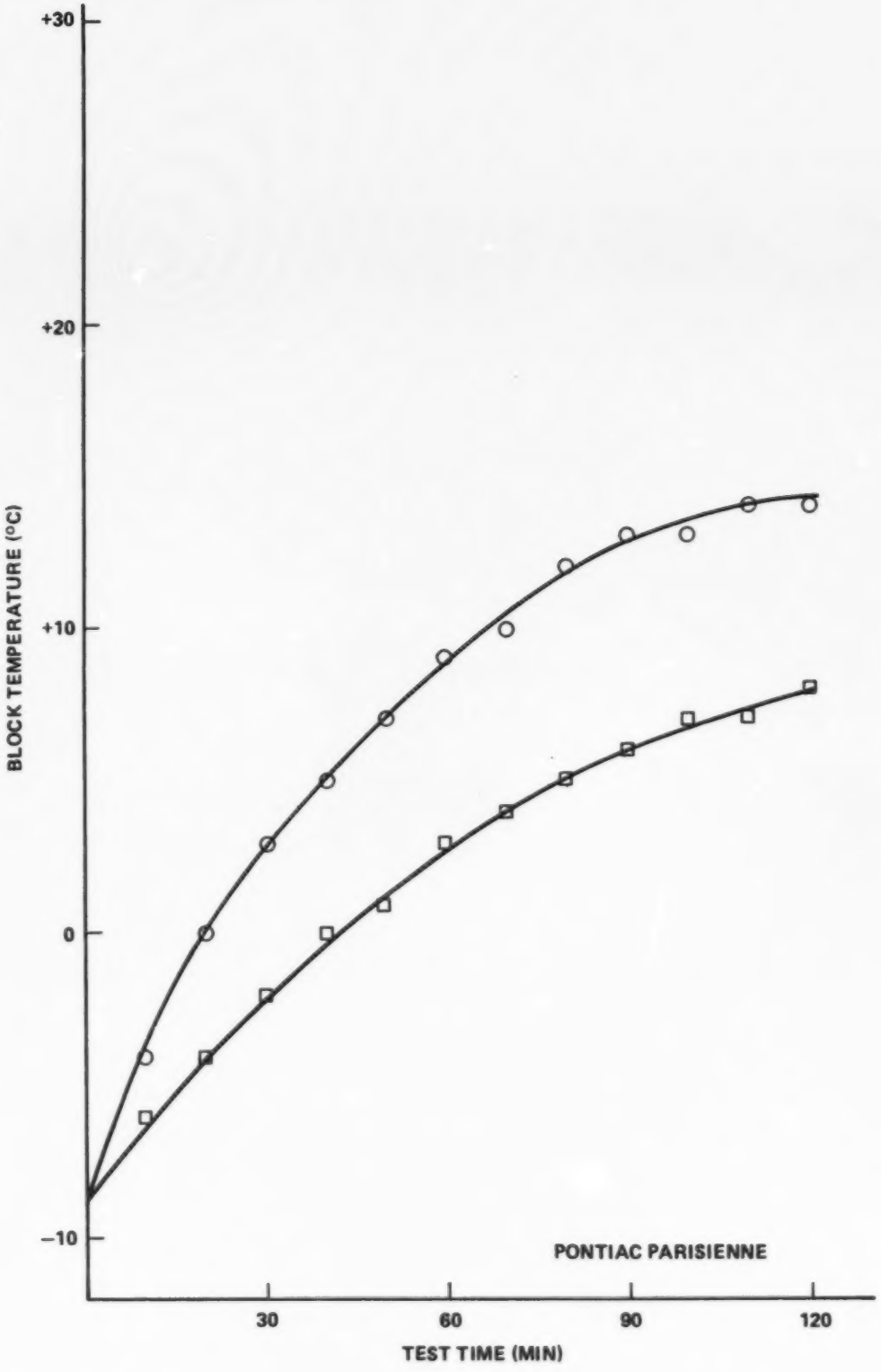
+30
+20
+10
0
−10
BLOCK TEMPERATURE (°C)
PONTIAC PARISIENNE
30
60
90
120
TEST TIME (MIN)

Figure 17

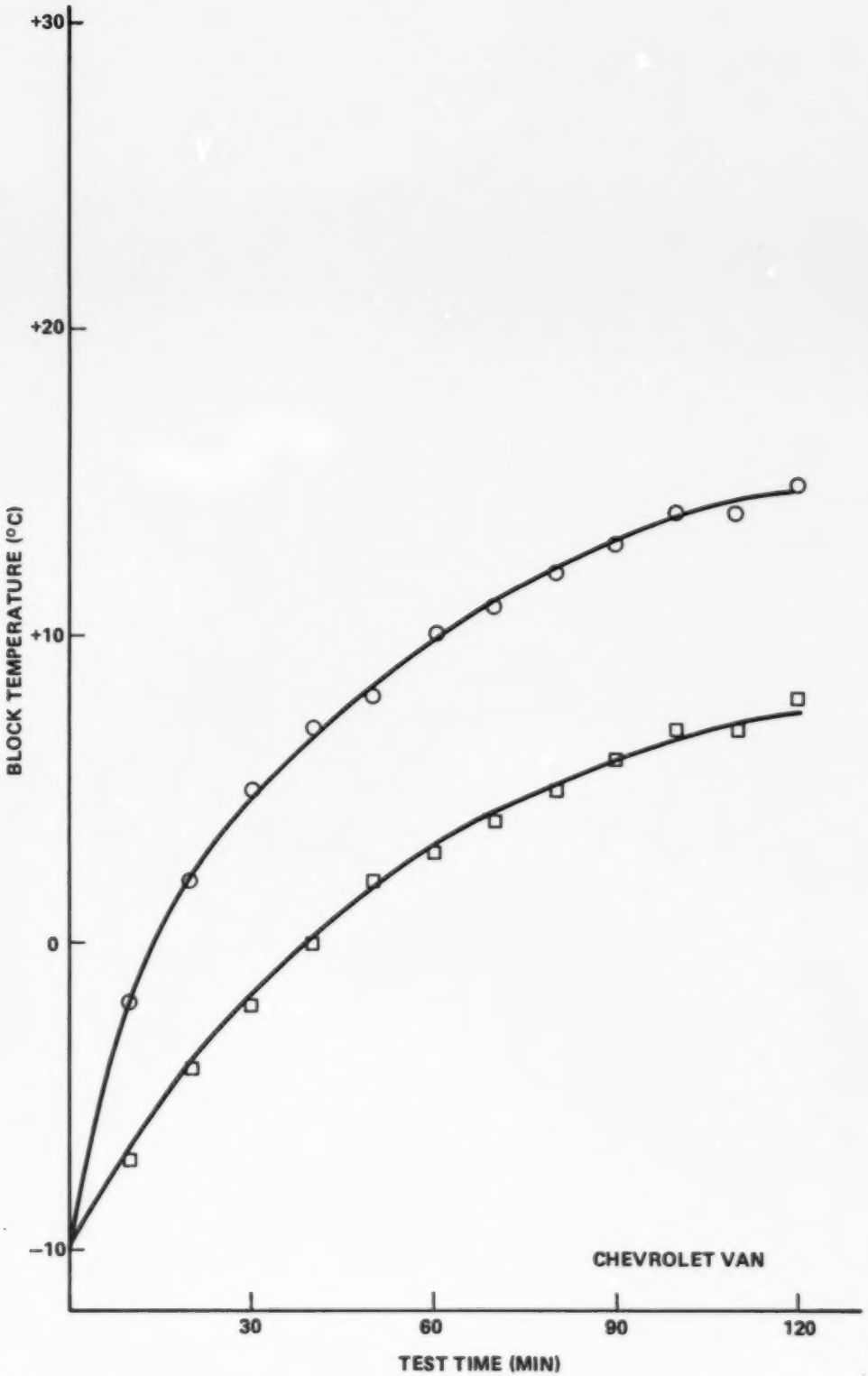
+30
+20
+10
0
−10
BLOCK TEMPERATURE (°C)
CHEVROLET VAN
30
60
90
120
TEST TIME (MIN)

Figure 18

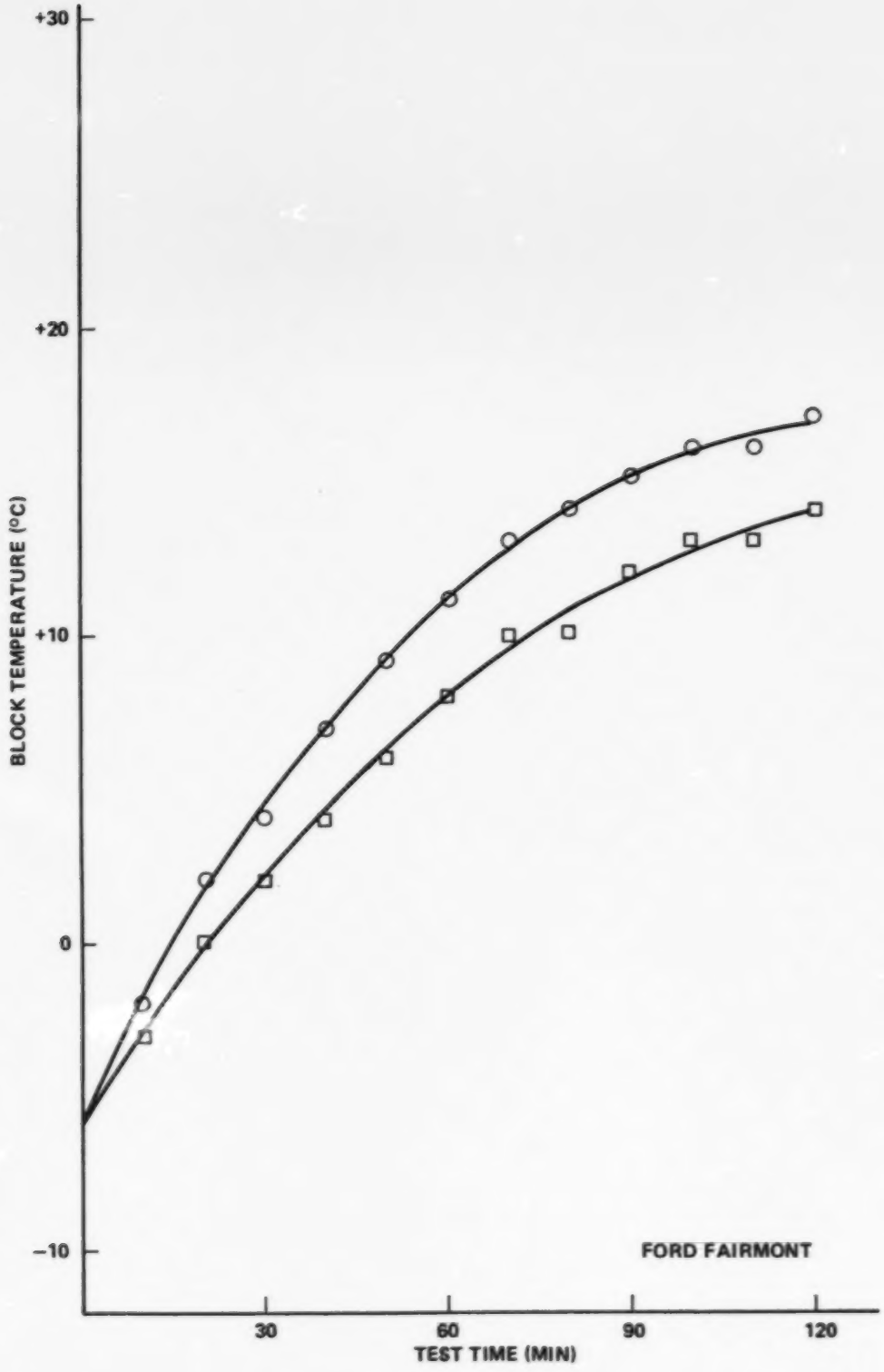
+30
+20
+10
0
−10
BLOCK TEMPERATURE (°C)
FORD FAIRMONT
30
60
90
120
TEST TIME (MIN)

Figure 19

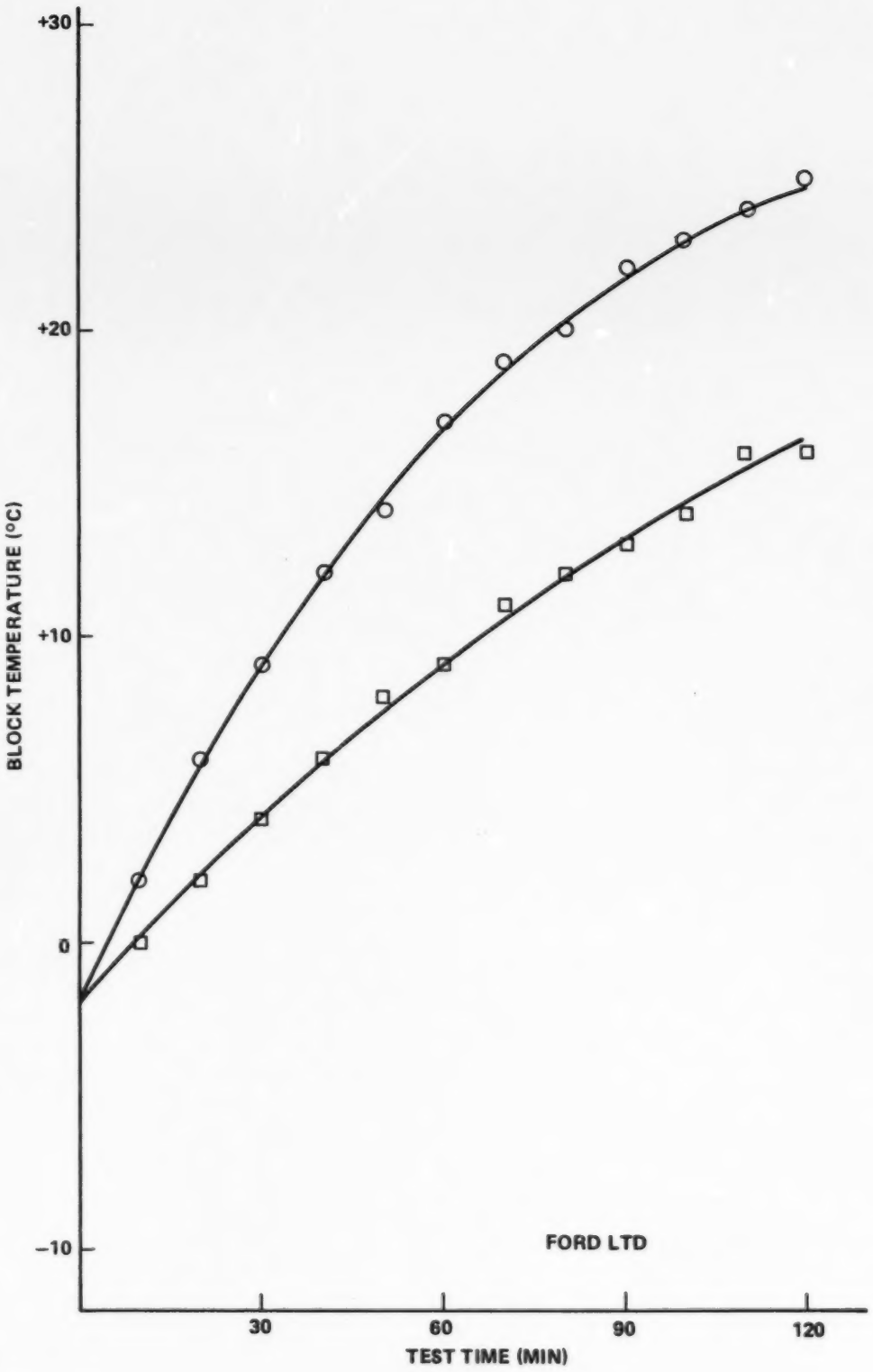
+30
+20
+10
0
−10
BLOCK TEMPERATURE (°C)
FORD LTD
30
60
90
120
TEST TIME (MIN)

Figure 20

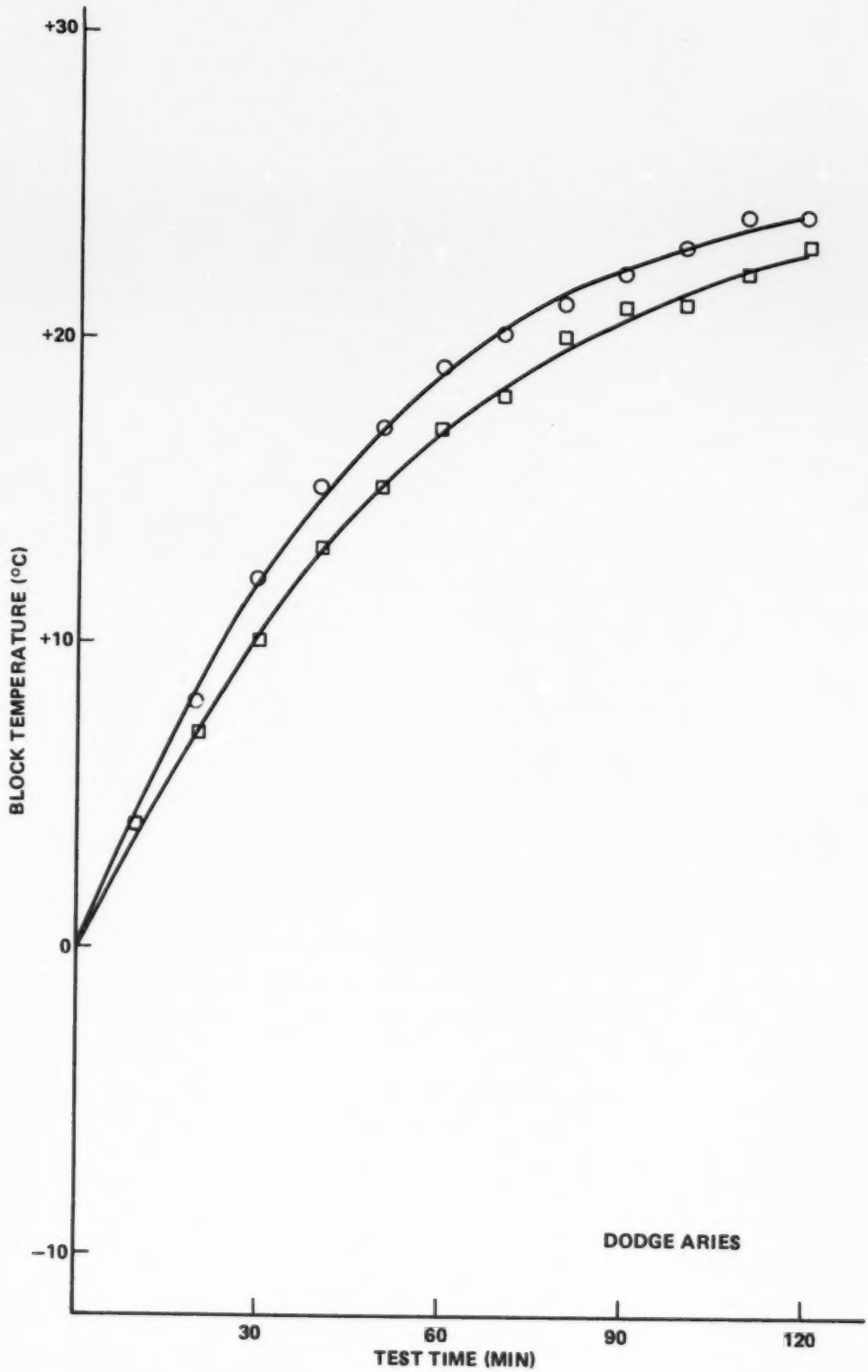
+30
+20
+10
0
−10
BLOCK TEMPERATURE (°C)
DODGE ARIES
30
60
90
120
TEST TIME (MIN)

Figure 21

FIGURES A.1 to A.4

Title: Time-Variation of Vehicle and Engine Parameters During a Typical Cold-Start Test

Explanations: The measured parameters are vehicle speed (rpm), manifold vacuum (in Hg), vehicle speed (mph), ambient temperature (°C), block temperature (°C), engine oil temperature (°C), carburetor inlet temperature (°C), underhood temperature (°C), and relative choke position (V).

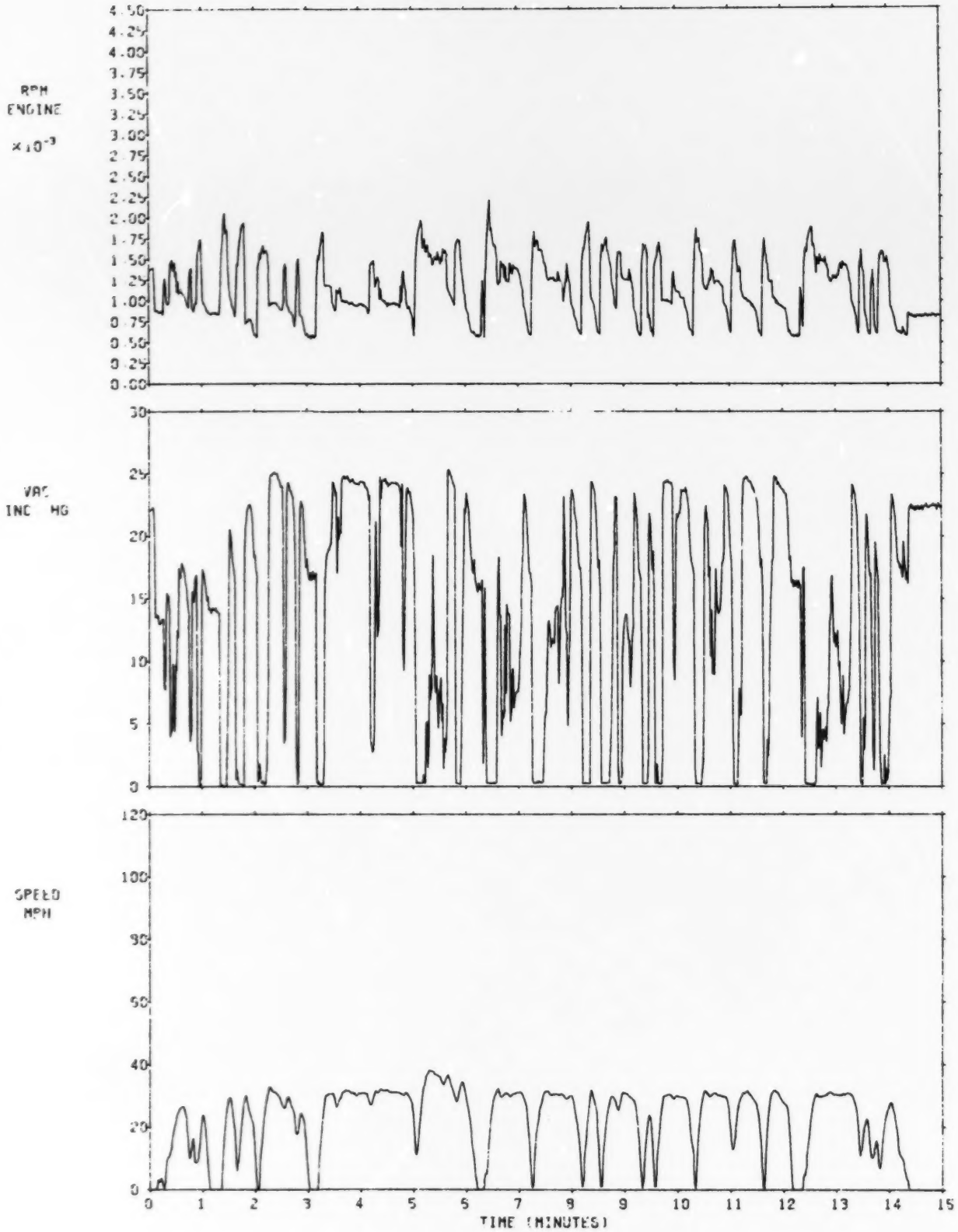
RPM
ENGINE
x10⁻³
4.50
4.25
4.00
3.75
3.50
3.25
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
VAC
INC HG
30
25
20
15
10
5
0
SPEED
MPH
120
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
TIME (MINUTES)

Figure A.1

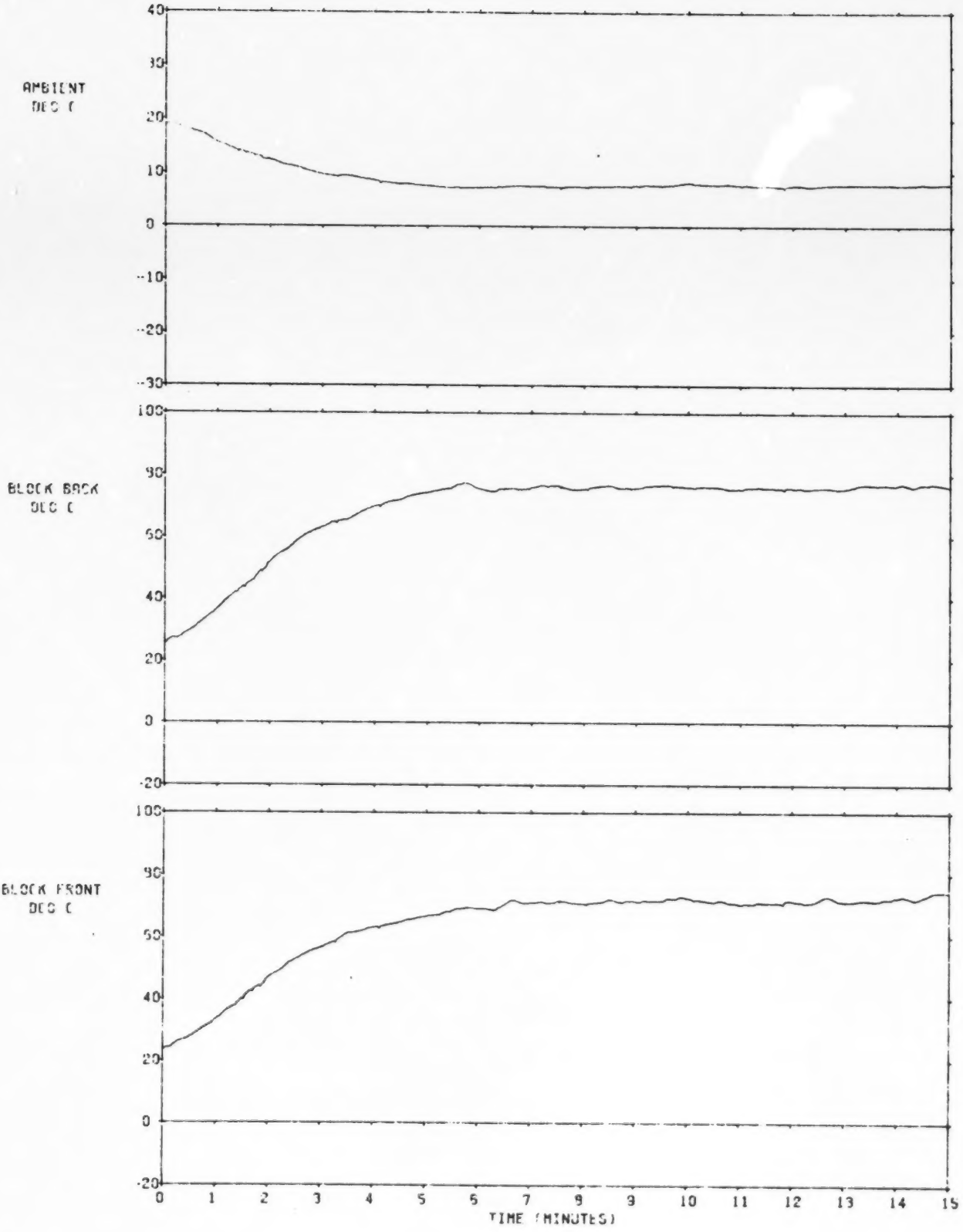
AMBIENT
DEG C
40
30
20
10
0
-10
-20
-30
BLOCK BACK
DEG C
100
90
80
40
20
0
-20
BLOCK FRONT
DEG C
100
90
80
40
20
0
-20
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
TIME (MINUTES)

Figure A.2

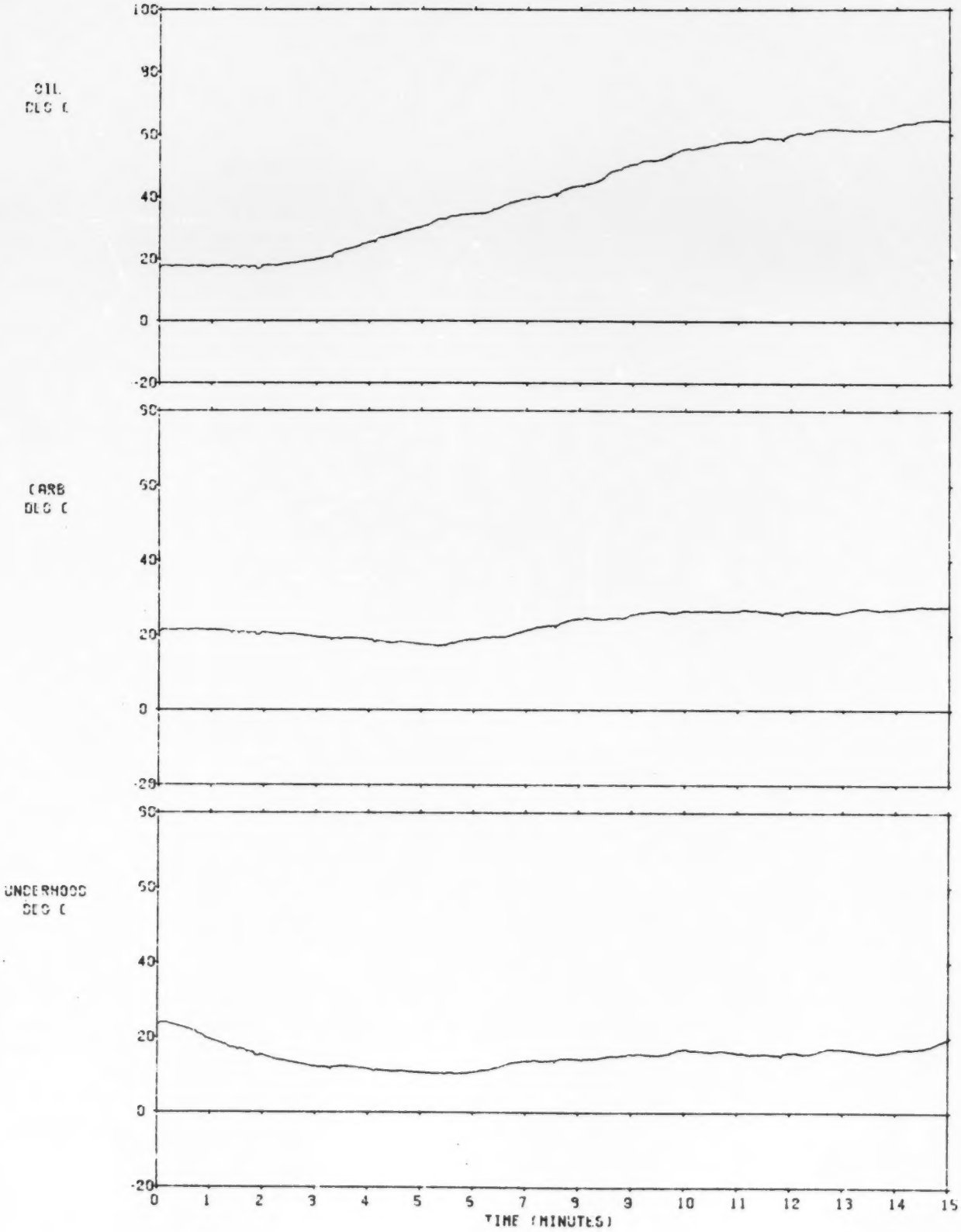
OIL
DEG C
100
80
60
40
20
0
-20
CARB
DEG C
60
40
20
0
-20
UNDERHOOD
DEG C
60
40
20
0
-20
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
TIME (MINUTES)

Figure A.3

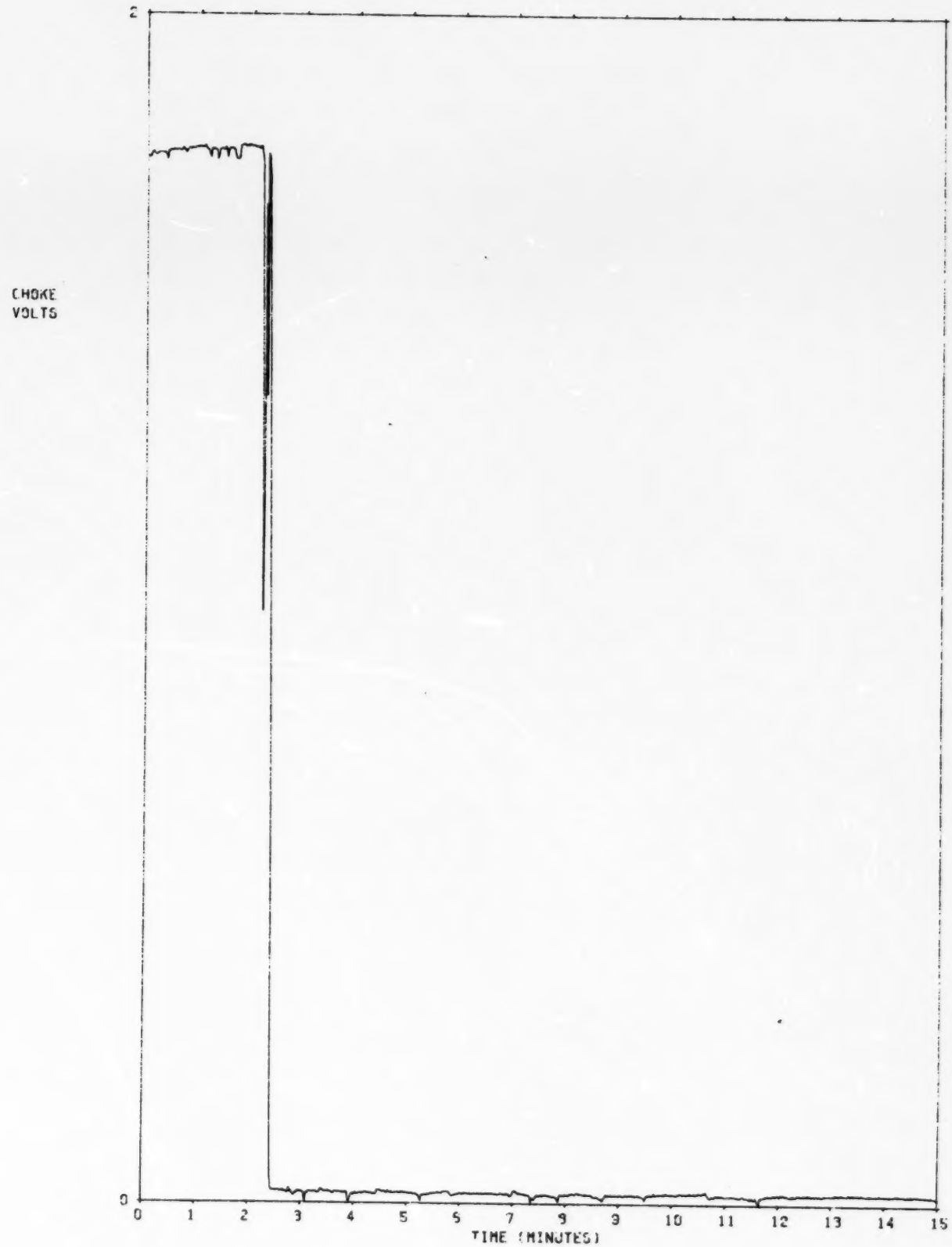

Figure A.4

FIGURES A.5 to A.8

Title: Time-Variation of Vehicle and Engine Parameters During a Typical Warm-Start Test

Explanation: The measured parameters are vehicle speed (rpm), manifold vacuum (in Hg), vehicle speed (rpm), ambient temperature (°C), block temperature (°C), engine oil temperature (°C), carburetor inlet temperature (°C), underhood temperature (°C), and relative choke position (V).

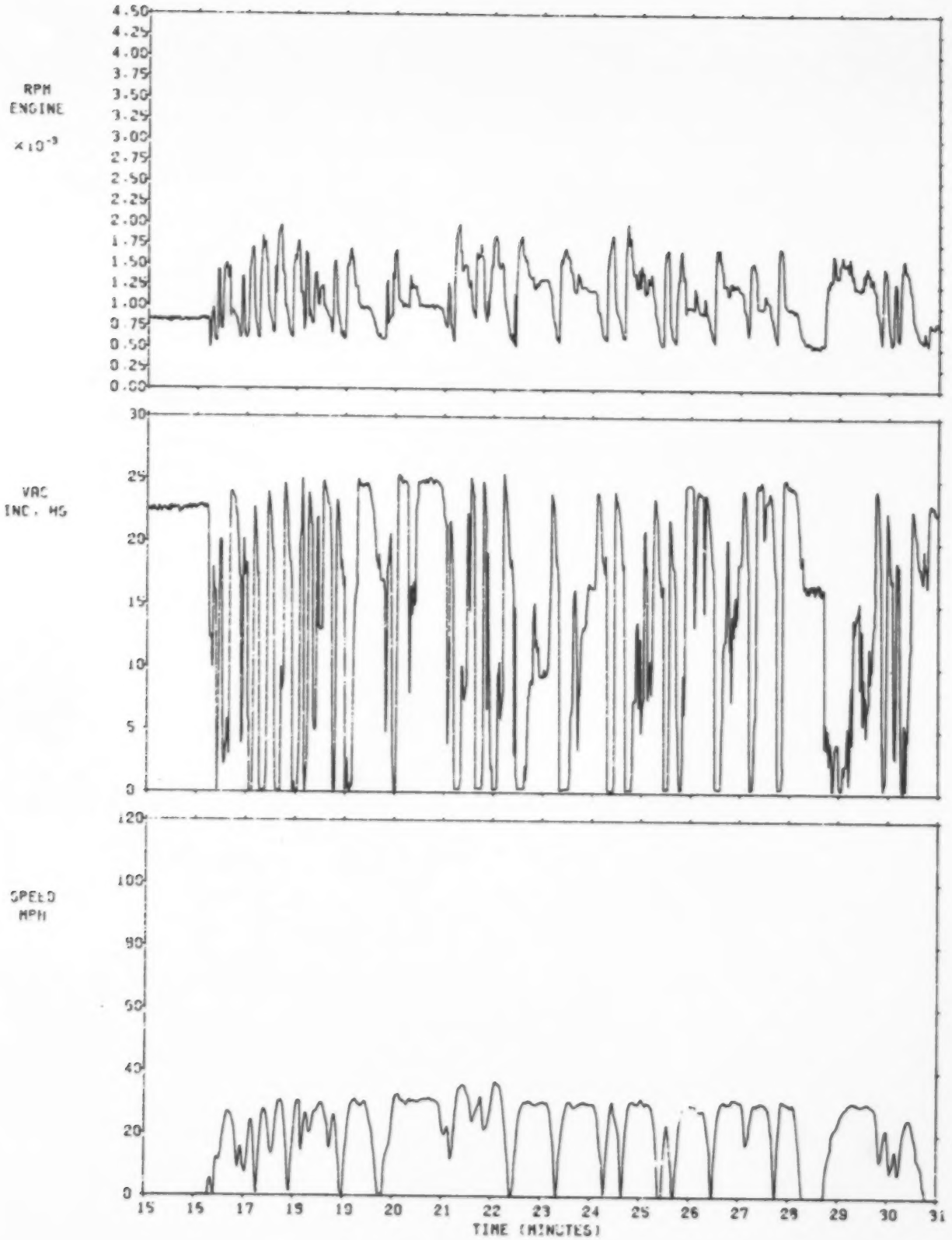
RPM
ENGINE
x10⁻³
4.50
4.25
4.00
3.75
3.50
3.25
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
VAC
INC. HG
30
25
20
15
10
5
0
SPEED
MPH
120
100
80
60
40
20
0
15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
TIME (MINUTES)

Figure A.5

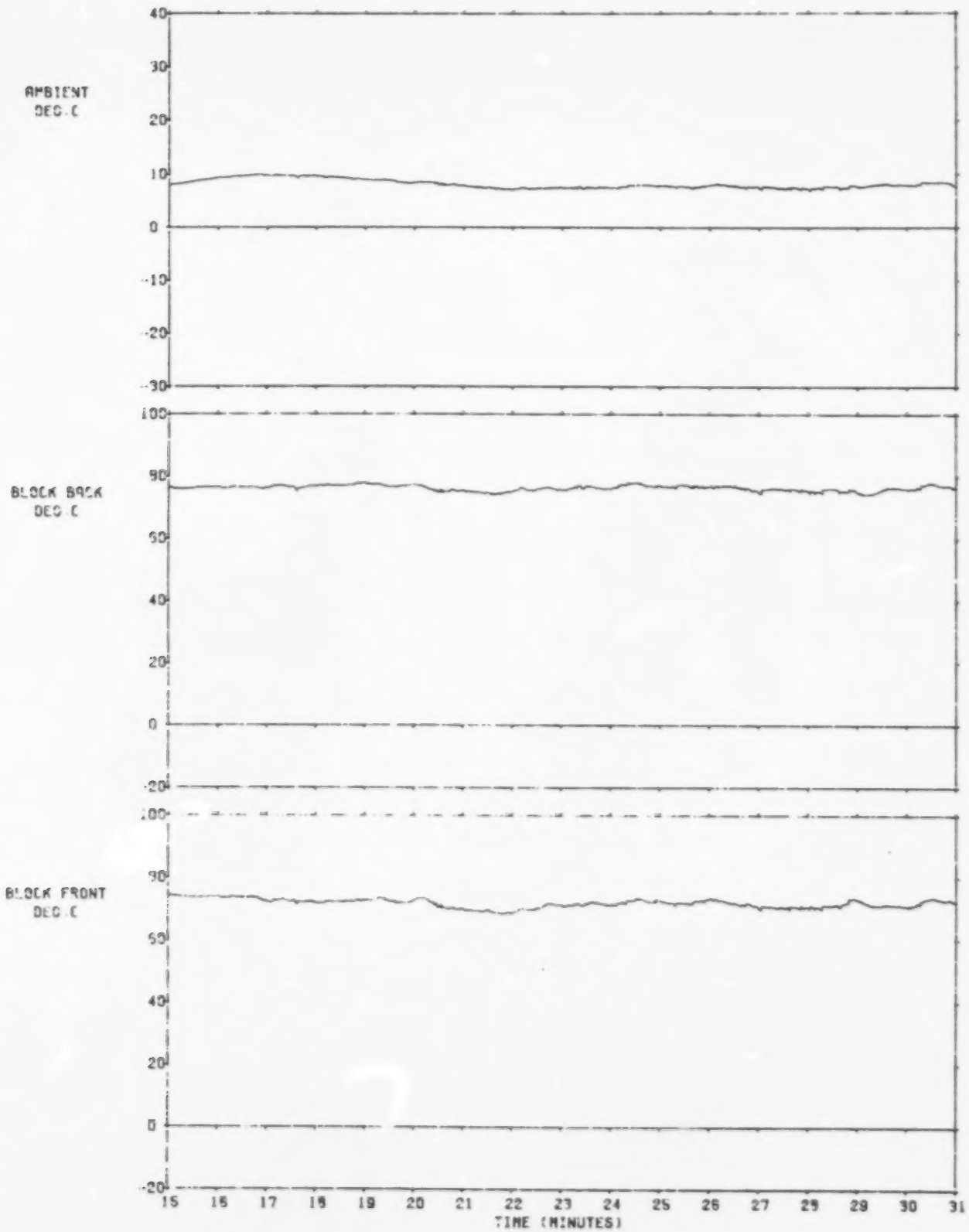
AMBIENT
DEG.C
BLOCK BACK
DEG.C
BLOCK FRONT
DEG.C
40
30
20
10
0
-10
-20
-30
100
90
80
40
20
0
-20
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
TIME (MINUTES)

Figure A.6

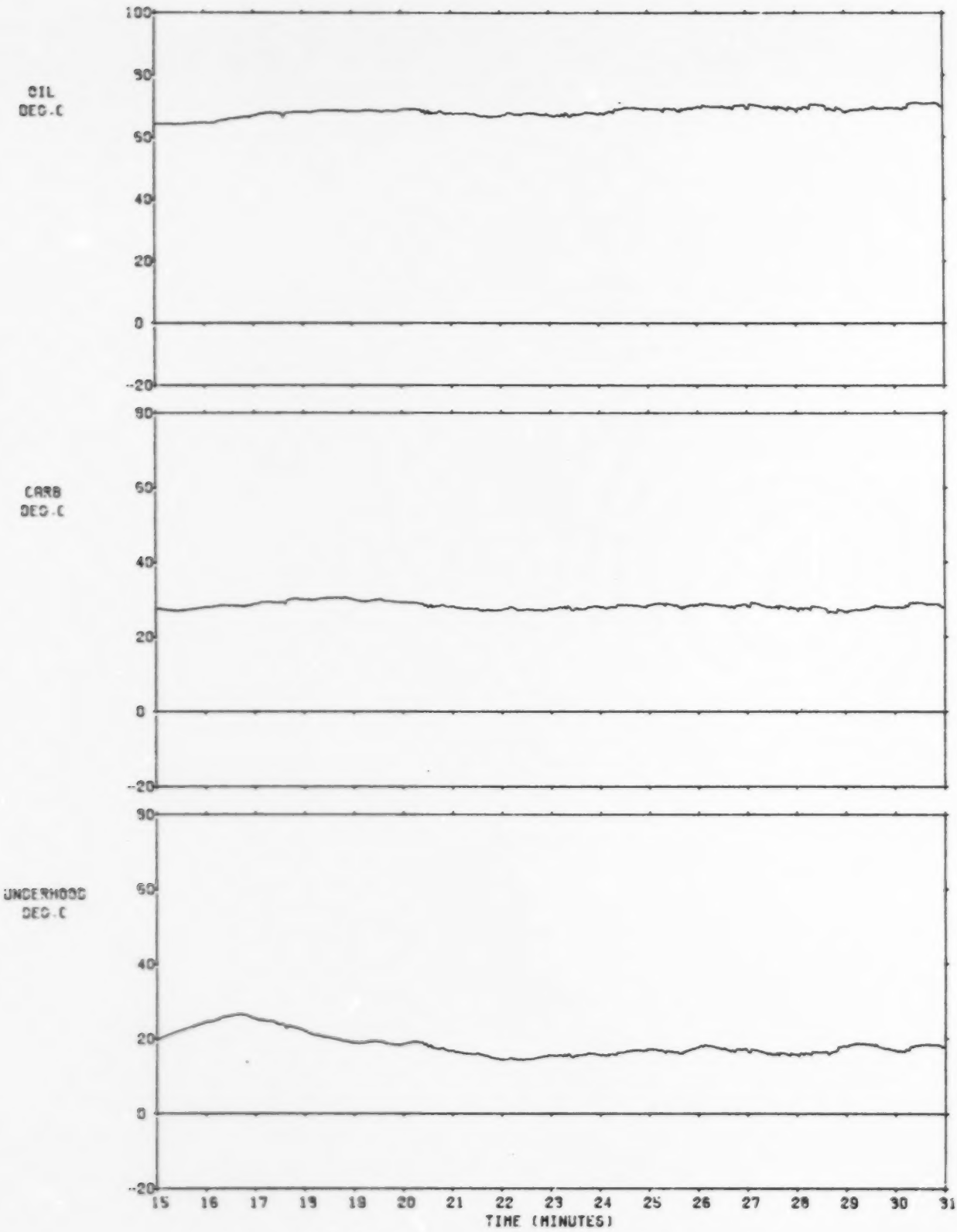
OIL
DEG.C
100
90
60
40
20
0
-20
CARB
DEG.C
80
60
40
20
0
-20
UNDERHOOD
DEG.C
80
60
40
20
0
-20
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
TIME (MINUTES)

Figure A.7

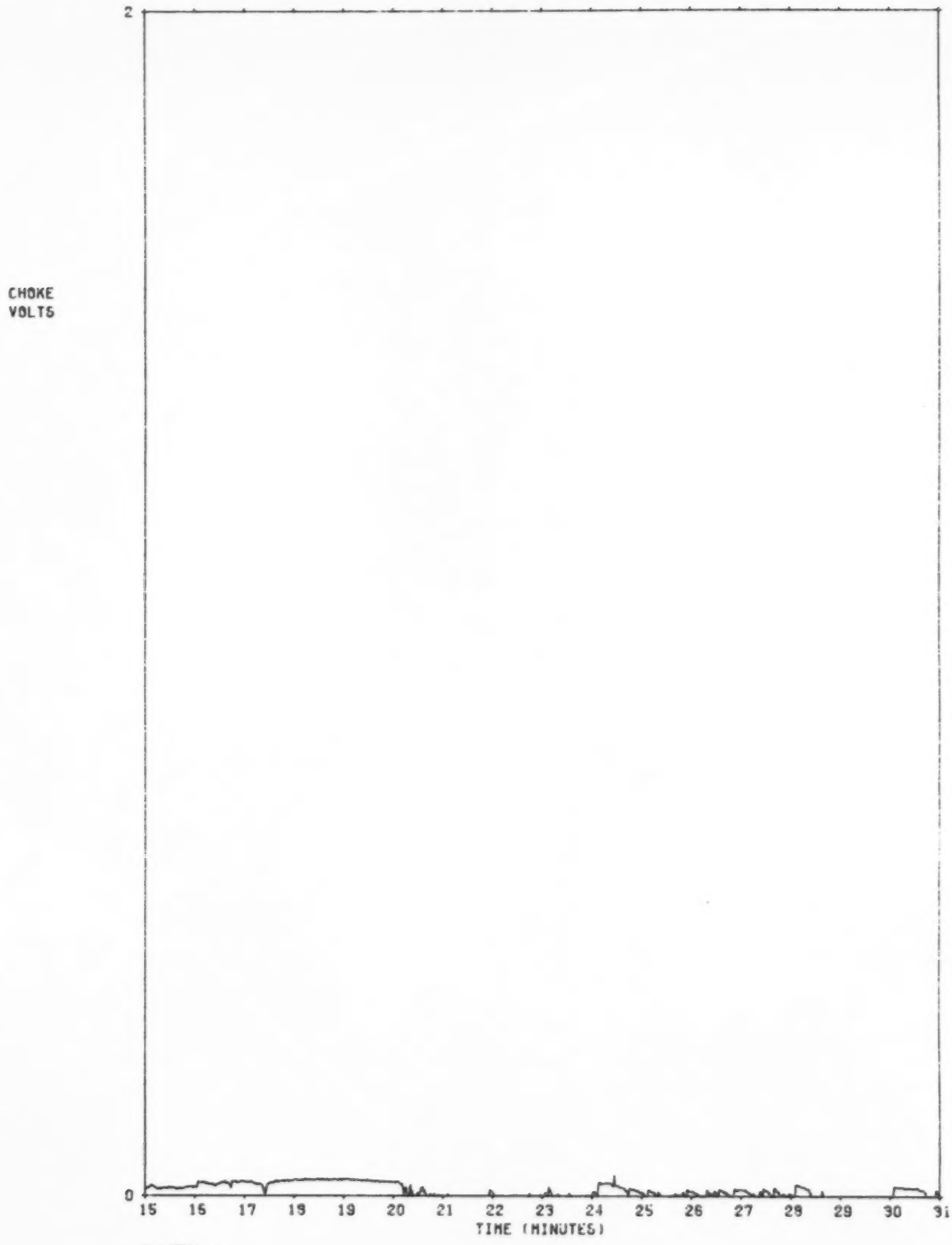
2
CHOKE
VOLTS
0
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
TIME (MINUTES)

Figure A.8